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UDR-TR-88-10

THE COLLECTION OF NON-CONUS AIRCRAFT ICING DATA ALONG WITH AN IDENTIFICATION OF THE GEOGRAPHICAL AREAS OF POTENTIAL SEVERE ICING AND A STUDY OF A METHOD OF REMOTE DETERMINING ATMOSPHERIC ICING DATA

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prepared for

Department of Transportation
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Contract No. DTFA03-85-C-00009

The University of Dayton

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FOREWORD

This final technical report describes the work accomplished during the period 24 April 1985 to 30 November 1987 by the University of Dayton Research Institute (UDRI) under Contract Number DTFA03-85-C-00009 for the Federal Aviation Administration. Mr. Ernest Schlatter was the technical contract monitor.

Cooperation and assistance from a number of individuals and organizations was vitally important to the success of the program. Mr. P. Thorson of ETAC and his colleagues provided contour map data from the ETAC data base. Dr. R. K. Jeck of NRL provided a great deal of input for the collection of the data as well as providing data for validating the Smith-Feddes model. Mr. C. W. Rogers of Calspan provided the computer code and user's documents for the updated Smith-Feddes model.

Ms. Joanda D'Antuono was responsible for typing and assembling this report.

ABSTRACT

Realistic methods are discussed for identifying potentialy severe icing geographical regions of the Northern Hemisphere. A useful method to calculate the liquid water content of a remote region (using satellite data) is described. The collection of non-conus aircraft is shown and data is presented.

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SECTION 1
INTRODUCTION

This is the the final report detailing the work accomplished under Contract DTFA03-85-C-00009 for the Federal Aviation Administration (FAA). Essentially the contract requested research in these three areas:

1) Survey foreign countries and retrieve whenever possible aircraft icing data that would be suitable for inclusion into the already established FAA/NRL icing data base.

2) Determine those geographical areas where icing would be a problem for aircraft.

3) Develop an alternate data collection scheme which could be used in lieu of flying aircraft to obtain icing data.

1.1 BACKGROUND OF AIRCRAFT ICING DATA

The current FAA/NRL icing data base is used to characterize the potential icing environment thru which aircraft fly. One main purpose of this data base is to predict maximum icing conditions, so that the proper cautionary measures can be taken. Curently, this data base is primarily from the continental United States. It was the desire of the FAA to broaden the data base to include data from other parts of the world.

The main problem in attaining icing data from other countries was that few foreign countries had programs that utilized aircraft to collect data on liquid water content, median volume diameter and other parameters for the express purpose of assembly-ing the data into a data base similar to that of the FAA's; France and South Africa being the only two.

Nonetheless other countries such as Canada had programs in cloud seeding from which data could possibly be used by the FAA. England had three agencies which had data that could possibly have proven useful to the FAA, Australia, and Russia had possible programs, Germany had a program that originally looked promising,

and finally the JTD Environmental Company located in Vasendera, California performed icing certification work for foreign countries. These countries and company were possible sources for the FAA/NRL icing data base. Data which proved applicable to the FAA/NRL data base was obtained from the sources shown in Table 1.1.

Four steps were required for obtaining non-continental United States (non-conus) icing data.

1. Construct a mailing list of all agencies thought to have icing data. The rule was - if in doubt send a letter.
2. Use the response of the original letters for new mailing or further contact if the initial response was favorable.
3. When data was located, determine the group in the agency and a name in the group who had the authority to send UDRI the data.
4. Make the proper arrangements for the data to be sent to UDRI in the desired format.

Step one was relatively easy due to the work done by Dr. Jeck of the NRL in alerting UDRI to those agencies who had data. The results of Steps 2, 3, and 4 are summarized by country in Appendix A. Data that has been received from foreign countries that will be considered for inclusion in the FAA/NRL data base are summarized in Table 1.1 of Section 1.1. Data received in summary form that will not find its way into the data base appears in Table 1.2 of the same section. Appendix A list the complete mailing list as well as the responses. Appendix B is a replica of the letters sent.

Table 1.1 is a listing in summary form, delineated by country and agency, of the data received by UDRI during this contractural effort. Data was received from Canada (two agencies), the JTD Environmental Services, the South African Weather Bureau,

TABLE 1.1

SUMMARY OF COLLECTED FOREIGN DATA

DATA FROM ALBERTA RESEARCH COUNCIL
ALL FLIGHTS MADE IN NORTHERN CANADA

1983-Winter

Date	Temp Range °C	Alt Range kft.	MVD Range micron	Max. LWC J.W. grams/m³	Max. LWC FSSP grams/m³	Distance in clouds km	Time in clouds min	Type of† Clouds
14/03	-10,-14	09,11	02,45	.37	.97	71	27.3	SC/CU/TCU
15/03	-13,-15	10,12	02,45	.40	.84	96	35.7	SC/CU/TCU
16/03	-15,-20	10,13	02,45	.45	.71*	224	56.8	SC
17/03	-17,-21	11,13	02,45	.34	.61*	63	20.3	SC/AC
21/03	-11,-22	11,13	02,45	.32	.30*	25	15.3	AS/ST
22/03	-11,-15	05,11	04,45	.39	.32*	84	21.8	SC/AS
23/03	-01,-14	06,11	02,45	1.60	1.39*	145	48.2	TCU/SC
24/03	-09,-18	07,13	02,45	.62	.93*	189	59.2	CU/TCU

1983-Summer

Date	Temp Range °C	Alt Range kft.	MVD Range micron	Max. LWC J.W. grams/m³	Max. LWC FSSP grams/m³	Distance in clouds km	Time in clouds min	Type of† Clouds
16/05	-06,-10	10,11	02,31	.73	.76*	98	28.3	CU/TCU
31/05	-03,-14	12,16	02,31	.86	.66*	120	32.0	CU/TCU
01/06	-01,-08	00,09	02,45	.90	.80	4	6.8	CU/TCU
06/06	-04,-10	12,15	02,31	.89	.77	117	30.2	CU/TCU
08/06	00,-11	10,15	02,31	1.18	1.25*	61	15.7	TCU/CB
09/06	-10,-12	14,15	04,31	1.00	1.22	199	48.4	TCU/CB
10/06	-04,-13	12,15	02,31	.65	1.15	149	40.0	CU/TCU
11/06	-07,-12	11,13	02,31	.74	1.06	53	16.9	CU/TCU
12/06	-01,-11	09,13	02,31	.87	1.18	62	18.3	CU/TCU
19/06	03,-09	06,09	02,45	.46	.73*	54	19.2	ST/AS/NS
21/06	-05,-10	11,13	05,45	1.33	1.73*	72	10.1	CU/TCU
22/06	-03,-13	08,15	07,45	1.17	2.03	48	12.5	TCU/CB
29/06	-07,-11	14,15	08,31	.98	.90*	19	4.8	CU/TCU
30/06	00,-05	10,13	08,31	.65	.66	60	23.0	ST/AS/NS
03/07	-07,-11	10,15	05,45	.84	1.22*	59	14.1	TCU/CB
07/07	-09,-11	16,17	02,31	.09	.08*	11	3.1	TCU/CB
08/07	00,-12	11,18	03,31	.53	.60	16	4.5	TCU/CB
12/07	00,-12	11,16	02,31	1.50	1.70	109	25.2	TCU/CB
17/07	-07,-11	12,15	02,31	1.73	.80*	75	18.1	TCU/CB
21/07	00,-11	10,15	02,31	1.48	1.55	88	22.9	TCU/CB
26/07	03,-12	08,16	02,31	1.14	1.27*	51	13.1	TCU/CB
28/07	02,-11	10,16	02,31	1.02	1.12*	53	13.3	TCU/CB

† SC-stratocumulus, CU-cumulus, AC-altocumulus, AS-altostratus, ST-stratus, CB-cumulonimbus, NS-nimbostratus, TCU-subset of cumulus, e.g. cumulus-conjectus, ICON-? designation used by ARC.

Table 1.1 (continued)

Date	Temp Range °C	Alt Range kft.	MVD Range micron	Max. LWC J.W. grams/m^3	Max. LWC FSSP grams/m^3	Distance/Time in clouds km	Distance/Time in clouds min	Type of Clouds
01/08	-08,-13	17,18	02,31	1.29	1.09	86	21.9	TCU/CB
03/08	-01,-13	12,18	02,31	1.36	1.34	77	21.1	TCU/CB
14/08	-09,-13	15,16	02,31	.67	.71*	51	16.4	TCU/CB
15/08	-06,-12	15,16	02,31	.76	.74*	88	18.8	TCU/CB
16/08	-07,-11	09,16	02,31	1.22	1.07	66	15.0	TCU/CB
17/08	-01,-11	13,16	02,31	1.27	.71*	99	21.4	TCU/CB
18/08	-09,-10	13,14	08,31	.07	.09*	26	5.6	ST/AS/NS
24/08	-02,-10	12,16	02,31	1.04	.82	90	21.2	CT/TCU
28/08	03,-10	11,16	02,31	1.79	.89	152	38.1	CT/TCU
				1983-Winter				
28/11	-07,-20	04,11	02,31	.12	.19*	18	22.7	No Information
08/12	-15,-20	11,14	07,31	.39	.30	214	61.4	AS/AC
09/12	00,-20	05,07	01,16	.97	.31	8	9.0	AS/AC
10/12	-04,-17	05,13	01,15	.98	.39*	258	65.8	AS/AC
28/12	-07,-20	04,11	02,31	.21	.18*	19	18.0	No Information
				1984-Winter				
01/02	-15,-22	11,14	02,31	.29	.25*	138	34.2	CU
02/02	-21,-22	14,15	20,31	.15	2.75*	4	1.8	No Information
06/02	-14,-19	13,15	12,31	.06	.48*	7	1.9	AC
08/02	-08,-10	11,12	10,31	.37	.26*	125	29.0	CU
09/02	-11,-22	11,16	02,31	.38	.68	135	50.8	CU
10/02	-16,-22	11,13	02,31	.37	.44	259	83.7	AC
11/02	-03,-15	04,11	02,31	.57	.08	10	3.0	CU
12/02	-03,-18	06,15	10,31	.22	.32	133	33.9	CU
13/02	-09,-19	11,15	04,31	.19	.24	217	51.3	CU
				1984-Summer				
13/06	-07,-11	12,14	02,12	.99	.64*	34	10.1	CU/TCU
15/06	00,-11	08,15	02,31	2.17	1.39	35	8.6	TCU/CB
19/06	03,-13	05,13	02,31	4.25	1.52*	24	6.7	CU/TCU
20/06	02,-10	08,14	02,31	4.02	1.10*	60	15.6	CU/TCU
22/06	01,-11	07,14	02,31	2.24	1.10*	46	12.0	CU/TCU
24/06	00,-10	10,15	02,31	1.61	.86	131	33.2	TCU/CB
25/06	04,-11	08,14	02,31	3.38	1.31*	71	17.7	TCU/CB
29/06	-03,-13	13,18	09,31	1.16	1.12*	17	5.2	CU/TCU
02/07	-02,-15	10,15	02,31	1.35	.62	38	10.6	CU/TCU
04/07	04,-12	11,16	02,31	2.12	1.10	105	24.4	CU/TCU
05/07	00,-12	10,16	02,31	2.01	.65	72	12.0	TCU/CB
09/07	-01,-11	10,14	02,31	1.41	.79	99	25.7	CU/TCU
11/07	-06,-12	14,16	02,31	1.98	1.80	147	29.5	TCU/CB
12/07	05,-13	08,15	02,45	3.58	1.51*	178	37.9	TCU/CB

Table 1.1 (continued)

Date	Temp Range °C	Alt Range kft.	MVD Range micron	Max. LWC J.W. grams/m³	Max. LWC FSSP grams/m³	Distance/Time in clouds km	Distance/Time in clouds min	Type of Clouds
13/07	-06,-10	12,14	02,31	2.22	1.15*	32	9.9	CU/TCU
17/07	04,-10	10,16	02,31	2.80	1.56*	106	21.6	TCU/CB
19/07	-09,-10	14,16	12,31	2.43	1.10*	16	3.4	TCU/CB
27/07	-04,-10	16,18	02,31	1.14	.75	80	22.7	CU/TCU
28/07	-02,-10	13,17	02,31	3.35	1.18*	174	43.3	TCU/CB
30/07	01,-01	12,16	12,31	1.73	1.62*	72	16.0	TCU/CB
03/08	05,-03	10,14	04,08	.03	.06	2	1.2	CU/TCU
04/08	04,-01	10,17	04,31	1.27	1.60*	56	14.8	CU/TCU
05/08	00,-11	13,17	02,31	1.95	1.32*	65	20.5	TCU/CB
06/08	00,-12	13,17	04,45	3.42	1.90	128	31.4	TCU/CB
09/08	-05,-12	15,17	02,45	.62	.61*	81	20.5	CU/TCU
10/08	-02,-02	13,13	14,31	.31	.08*	2	0.4	CB
13/08	-05,-11	08,15	02,31	2.68	1.58*	157	40.1	CU/TCU
14/08	04,-05	07,12	02,31	1.01	.91*	68	20.9	CU/TCU
17/08	-08,-10	12,17	02,31	1.01	.67	56	14.1	TCU/CB
18/08	05,-11	13,17	06,31	2.69	1.08	95	17.8	TCU/CB
20/08	-05,-15	11,16	04,31	.90	.52*	31	11.0	CU/TCU
24/08	03,-13	10,16	02,31	2.78	4.77	118	27.8	TCU/CB
25/08	-05,-10	12,14	02,31	.67	.59	88	17.7	CU/TCU
				1985-Summer				
03/06	-02,-10	09,13	02,31	.88	1.18	41	12.5	CU/TCU
06/06	-09,-10	12,13	02,45	.57	.89*	112	27.4	CU/TCU
10/06	-10,-16	10,12	02,45	.45	.82*	42	11.3	CU/TCU
12/06	-03,-15	11,17	02,45	1.42	2.04	176	43.6	CU/TCU
15/06	-01,-16	05,15	02,31	.55	1.35	178	50.2	CU/TCU
20/06	00,-11	08,13	02,31	2.54	2.57	137	35.8	CU/TCU
23/06	00,-15	09,16	05,31	2.12	1.88	93	21.0	TCU/CB
24/06	02,-15	05,14	02,31	1.39	1.69*	118	32.0	CU/TCU
25/06	-01,-11	08,12	02,31	.96	1.28*	103	31.0	CU/TCU
27/06	-07,-10	13,15	06,31	.46	.60*	31	7.8	CU/TCU
28/06	-10,-11	15,16	08,31	.79	1.00*	23	6.3	CU/TCU
30/06	-05,-12	14,16	02,31	.86	.73*	38	10.1	CU/TCU
01/07	00,-10	13,16	02,31	2.07	1.99	82	23.0	CU/TCU
05/07	-04,-10	13,17	02,31	1.66	1.68*	16	6.2	TCU/CB
10/07	00,-12	14,16	02,31	1.25	1.32*	107	28.7	CU/TCU
11/07	-04,-12	14,16	02,31	2.65	2.63*	156	35.2	CU/TCU
12/07	00,-20	09,20	02,31	2.10	2.27	179	46.6	CU/TCU
13/07	03,-13	09,14	02,31	1.82	2.41*	145	41.0	CU/TCU
15/0	-05,-12	12,14	02,31	1.94	2.64	108	35.6	CU/TCU
17/07	03,-12	06,14	02,31	2.54	2.91*	110	31.0	CU/TCU
18/07	00,-11	10,15	02,31	1.68	1.77*	113	27.9	CU/TCU
22/07	01,-16	11,20	02,31	1.61	1.31*	155	43.9	CU/TCU
23/07	00,-10	11,18	02,31	3.25	3.10	62	15.9	TCU/CB
24/07	00,-11	09,16	02,31	2.01	2.34*	92	24.8	CU/TCU

Table 1.1 (continued)

Date	Temp Range °C	Alt Range kft.	MVD Range micron	Max. LWC J.W. grams/m^3	Max. LWC FSSP grams/m^3	Distance/Time in clouds km	Distance/Time in clouds min	Type of Clouds
29/07	00,-11	10,16	02,08	1.29	.40	209	61.3	CU/TCU
30/07	-02,-13	12,16	01,08	1.95	.01	90	25.1	TCU/CB
02/08	02,-11	11,17	02,31	2.06	2.03*	137	34.7	TCU/CB
03/08	-07,-11	15,17	05,31	1.90	1.77*	11	4.1	TCU/CB
04/08	-01,-13	13,18	06,31	2.57	2.42	96	22.4	TCU/CB
05/08	-04,-11	12,14	02,31	2.42	2.34*	152	37.3	CU/TCU
13/08	-04,-11	12,14	05,31	1.10	1.23*	103	28.3	CU/TCU
14/08	00,-01	10,10	10,31	.18	.07*	9	2.7	CU/TCU
30/08	-07,-10	12,15	02,31	2.55	2.22*	68	36.8	TCU/CB
DATA COLLECTED BY THE ATMOSPHERIC ENVIRONMENTAL SERVICE, CANADA								
Flights over London, Ontario in 1981								
30/09	01,-07	05,10	08,31	.19	.16*	17	4.0	SC
01/10	01,-13	01,10	04,31	1.23	1.68	262	58.4	SC
02/10	01,-07	02,08	07/31	.82	.52	321	72.0	SC
15/10	03,-05	07,10	08,31	.60	.53*	143	30.9	SC
04/11	-05,-11	04,06	06,31	.27	.38*	20	4.7	SC
05/11	-06,-13	02,11	05,31	1.61	2.34*	166	39.2	SC
06/11	01,-13	02,10	07,31	1.72	.55*	254	57.8	SC
10/11	-02,-06	05,06	11,31	.33	.18	85	18.0	SC
16/11	-02,-04	04,10	09,31	.51	.25*	72	15.5	SC
17/11	-05,-06	01,11	07,31	1.08	.97*	247	56.2	SC
19/11	-04,-05	03,04	07,31	1.07	.47	169	50.0	SC
20/11	-03,-09	00,10	07,31	.82	.96	389	94.5	SC
Data collected at North Bay Ontario, 1982								
29/06	-01,-04	05,07	10,31	1.05	.66*	14	3.5	SC,TCU
30/06	02,-14	07,14	17,31	2.52	.03	29	7.0	SC,TCU
01/07	-08,-14	12,15	09,31	.37	.31*	13	3.4	SC,TCU
02/07	05,-12	02,05	10,31	1.48	.92	176	46.5	SC,TCU
12/07	01,-02	10,10	14,31	.10	.02*	4	1.0	SC,TCU
14/07	-04,-16	03,16	05,31	2.73	1.61*	154	35.0	SC,TCU
27/07	-01,-13	04,11	05,31	2.97	1.36	141	34.5	SC,TCU
Data from Syracuse, New York, 1984								
19/10	-03,-05	10,14	07,31	1.97	1.27*	60	15.2	CU,ST
23/10	00,-01	05,05	07,31	.23	.18*	1	.3	CU,ST
29/10	06,-03	07,10	05,31	.89	.61*	145	35.3	CU,ST
31/10	-04,-06	03,05	07,31	.54	1.76	232	64.4	CU,ST

Table 1.1 (continued)

Date	Temp Range °C	Alt Range kft.	MVD Range micron	Max. LWC J.W. grams/m^3	Max. LWC FSSP grams/m^3	Distance/Time in clouds km	Distance/Time in clouds min	Type of Clouds
02/11	-05,-11	03,07	07,31	1.80	.50	129	35.5	CU,ST
05/11	-10,-13	00,14	06,31	.76	1.06	296	84.0	CU,ST
06/11	-07,-13	05,08	06,31	.69	.43*	96	25.3	CU,ST
09/11	-03,-11	04,12	07,31	.79	.64	370	97.8	CU,ST
10/11	-09,-09	03,14	07,31	.87	.66*	170	43.7	CU,ST
11/11	-09,-14	02,14	05,31	.45	.43*	59	14.4	CU,ST
12/11	-07,-12	01,10	08,31	.73	.51*	178	48.8	CU,ST
13/11	-04,-09	02,06	10,31	.61	.65	176	49.5	CU,ST
Flights over North Bay Ontario in 1984								
20/01	-20,-23	03,03	07,31	.09	.05*	20	4.5	CU,ST
21/01	-20,-26	03,05	05,31	.01	.11*	16	3.7	CU,ST
30/01	-11,-18	03,08	11,31	.07	.06	17*	4.7	CU,ST
01/02	-13,-16	04,06	07,31	.15	.12*	8	2.1	CU,ST
02/02	-08,-09	04,06	09,31	.15	.23*	5	1.6	CU,ST
03/02	-03,-15	03,09	06,31	.46	.44	157	37.8	CU,ST
04/02	-05,-21	02,12	07,31	3.09	.51	107	26.3	CU,ST
07/02	-22,-26	09,11	11,31	.04	.08*	41	10.1	CU,ST
08/02	-09,-15	03,10	05,31	.12	.17*	94	23.9	CU,ST
09/02	-09,-11	06,08	17,24	.17	.32*	72	17.7	CU,ST
10/02	-03,-06	06,08	05,31	.22	.21*	193	45.9	CU,ST
13/02	-08,-10	03,14	05,34	.35	.37	77	17.9	CU,ST
14/02	02,-03	02,05	06,31	.39	.41	288	78.0	CU,ST
17/02	03,-07	03,11	05,31	.31	.39	284	71.9	CU,ST
19/02	04,-09	01,11	05,34	.28	.43	287	71.4	CU,ST
20/02	-05,-12	02,03	07,31	.35	.34	213	59.6	CU,ST
21/02	-11,-13	03,04	07,31	.10	.10*	125	34.2	CU,ST
24/02	50,-40	02,19	07,31	3.75	.15	144	41.4	CU,ST
28/02	-08,-14	02,13	05,33	.09	.06*	13	2.4	CU,ST
Flights over Halifax, Nova Scotia in 1986								
28/01	-04,-04	00,05	11,31	.60	.62	5	8.1	
30/01	-05,-40	00,03	08,61	.26	.29	117	28.9	
02/02	-05,-40	00,03	08,61	.26	.29	15	5.1	
05/02	00,-40	00,06	11,61	1.12	.49	154	39.3	
15/02	-01,-08	00,06	05,61	.02	.25	38	9.5	
18/02	-03,-40	00,07	07,31	.02	.17	274	71.0	
19/02	-05,-06	01,02	07,31	.02	.12*	7	1.8	
22/02	00,-12	00,09	10,33	.57	.64	603	109.2	
25/02	-01,-10	01,10	13,34	.25	.49	41	10.2	
26/02	-08,-40	00,08	05,33	.06	.59	300	51.1	
27/02	-08,-40	00,05	04,33	.12	.43	54	14.3	

Table 1.1 (continued)

Date	Temp Range °C	Alt Range kft.	MVD Range micron	Max. LWC J.W.	FSSP grams/m³	Distance/Time in clouds km	min	Type of Clouds
07/03	-02,-42	00,08	06,34	.65	.74	111	56.0	
10/03	-02,-15	01,11	07,34	.81	.26	261	59.8	
13/03	-06,-40	00,10	15,32	.03	.08*	7	8.3	

Twin Otter

Date	Temp Range °C	Alt Range kft.	MVD Range micron	Max. LWC J.W.	FSSP grams/m³	Distance/Time in clouds km	min	Type of Clouds
28/01	-03,-09	09,12	12,33	.00	.17*	12	2.7	SC
29/01	-07,-15	02,05	05,32	.37	.27*	39	10.2	SC
30/01	-03,-19	02,16	07,42	.12	.18*	34	7.4	SC
02/02	-04,-11	01,04	06,34	.32	.36*	12	3.5	SC
05/02	-02,-13	01,14	07,31	1.72	.55	60	14.4	SC
12/02	-03,-15	00,05	03,34	1.37	2.69	653	170.9	SC
14/02	-07,-15	00,03	07,32	.01	1.56	10	2.7	SC
15/02	-01,-20	00,16	07,31	.09	3.36	5	1.6	SC
18/02	-02,-05	04,09	07,33	.30	.40	156	37.7	SC
22/02	-04,-14	01,14	08,34	.29	.69*	344	79.6	SC
23/02	-03,-04	01,01	05,31	.00	.02	1	0.2	SC
24/02	-04,-15	02,09	10,31	.22	.49*	25	7.1	SC
25/02	-01,-09	00,05	07,33	.22	.46*	29	8.7	SC
26/02	-20,-22	12,13	07,31	.01	.08*	1	0.3	SC
27/02	-12,-15	05,06	07,31	.04	.14	2	0.6	SC
02/03	-02,-14	07,15	11,33	.29	.66	93	24.7	SC

DATA FROM JTD ENVIRONMENTAL SERVICES

FLIGHTS MADE IN NORTH SEA

1984-Winter

Date	Temp Range °C	Alt Range kft.	MVD Range micron	Max. LWC J.W.	FSSP grams/m³	Distance/Time in clouds km	min	Type of Clouds
22/02	-06,-07	02,03	09,14	.71	.35	150	42.0	ST
23/02	-09,-10	03,05	09,18	1.21	.55	124	28.0	ST
24/02	-05,-12	04,10	06,28	.43	.41	257	48.0	ST
01/03	-14,-15	04,11	15,30	.91	.36	197	30.0	ST
19/11	-06,-13	05,10	08,19	.52	.71	178	35.5	ST
20/11	-03,-06	03,06	13,19	.99	.98	229	47.0	ST
21/11	-08,-09	06,07	11,20	.46	.47	92	19.0	ST
22/11	-04,-07	06,07	09,14	.34	.32*	41	7.5	CU
23/11	-20,-22	17,18	19,30	.55	.41	121	20.5	CU
06/12	-09,-19	10,15	08,21	.36	.40	100	19.0	ST
18/12	-02,-07	03,08	09,39	.87	.78*	208	45.7	ST
19/12	-05,-13	05,08	12,17	.68	.66*	160	34.0	ST

Table 1.1 (continued)

Date	Temp Range °C	Alt Range kft.	MVD Range micron	Max. LWC J.W. grams/m³	Max. LWC FSSP grams/m³	Distance/Time in clouds km	Distance/Time in clouds min	Type of Clouds
				1985-Summer				
21/08	-05,-13	12,17	16,32	1.50	1.41*	306	51.8	CU
23/08	-04,-08	10,12	11,25	1.79	1.07	195	33.0	CU
26/08	-07,-13	11,14	10,27	1.25	.88*	338	62.0	CU
29/08	-08,-10	11,13	11,28	1.41	1.10*	278	51.0	CU
02/09	00,-12	10,14	12,27	1.37	.93*	93	18.0	CU
04/09	-09,-11	13,14	15,30	1.09	1.07*	31	5.5	CU
				1986-Winter				
11/18	-05,-07	08,09	17,27	2.22	.13*	103	20.0	ST/ICON

FLIGHTS MADE IN SWEDEN

Date	Temp Range °C	Alt Range kft.	MVD Range micron	Max. LWC J.W. grams/m³	Max. LWC FSSP grams/m³	Distance/Time in clouds km	Distance/Time in clouds min	Type of Clouds
				1985-Winter				
27/02	-06,-07	08,10	11,23	.47	.53	145	28.0	ST
28/02	-07,-11	08,10	09,30	.26	.22*	151	33.0	ST
01/03	-05,-11	03,07	10,21	.22	.41*	224	49.0	ST
08/03	-07,-10	03,04	10,13	.44	.47*	144	26.0	ST
13/03	-03,-05	02,03	08,19	.49	.58	195	44.0	ST
20/03	-05,-06	03,04	07,24	.69	.73*	168	38.0	ST
21/03	-11,-11	10,10	10,31	.40	.36	80	17.0	ST
26/03	-05,-07	05,08	08,34	.43	.36	206	45.0	ST
05/05	-04,-13	05,09	06,29	.50	.37*	177	30.0	CU
06/05	00,-06	05,09	06,16	.23	.19	83	12.5	ST
12/05	-08,-19	13,17	07,27	.35	.66	246	45.0	CU
13/05	-05,-12	13,17	17,28	.10	.04*	218	41.0	ST

FLIGHTS MADE IN SPAIN

Date	Temp Range °C	Alt Range kft.	MVD Range micron	Max. LWC J.W. grams/m³	Max. LWC FSSP grams/m³	Distance/Time in clouds km	Distance/Time in clouds min	Type of Clouds
				1986-Winter				
30/01	-14,-19	09,11	11,28	.48	.40	59	10.0	CU
01/02	-15,-16	12,13	18,27	.87	N/O	77	13.0	CU
12/02	-07,-08	11,12	08,14	.07	.02*	16	2.5	CU

FLIGHTS MADE IN IRELAND

Date	Temp Range °C	Alt Range kft.	MVD Range micron	Max. LWC J.W. grams/m³	Max. LWC FSSP grams/m³	Distance/Time in clouds km	Distance/Time in clouds min	Type of Clouds
				1986-Winter				
11/02	-05,-06	04,05	N/O	.50	N/O	198	39.0	ST/CU

Table 1.1 (continued)

Date	Temp Range °C	Alt Range kft.	MVD Range micron	Max. LWC J.W. grams/m^3	Max. LWC FSSP grams/m^3	Distance in clouds km	Time in clouds min	Type of Clouds
FLIGHTS MADE IN HOLLAND								
1986-Winter								
17/11	-05,-05	08,08	14,20	.22	.01	5	1.0	ST
FLIGHTS MADE IN NORWAY								
1986								
26/11	-10,-15	08,11	25,33	1.66	.64	135	26.0	CU
28/11	-05,-07	09,11	05,30	.24	.31	153	32.0	ST/ICON
29/11	-10,-13	07,08	17,30	1.04	.50	180	36.0	CU
DATA FROM SOUTH AFRICAN WEATHER BUREAU								
FLIGHTS OVER SOUTH AFRICA								
1984-Winter								
02/10	-10,-11	05,05	07,09	1.00	.01*	12	2.1	CU
03/10	-09,-10	05,05	07,11	1.50	.01*	21	3.5	CU
11/10	-12,-14	05,05	11,21	2.70	.05	32	5.1	CU
15/10	-14,-17	05,05	10,11	1.30	.10*	7	1.1	CU
17/10	-04,-14	05,05	07,08	.90	.10*	4	.7	CU
18/10	-10,-12	05,05	07,15	1.40	.30	28	4.4	CU
19/10	-09,-13	05,05	09,10	.07	.10	13	2.1	CU
22/10	-12,-15	05,05	08,22	1.50	.50	30	4.7	CU
23/10	-12,-13	05,05	09,15	.80	.20	20	3.0	CU
24/10	-09,-12	05,05	04,13	2.10	.50	29	4.1	CU
30/10	-10,-10	05,05	06,06	.01	.00	0	0	CU
07/11	-13,-14	05,05	10,11	1.00	.00	2	.3	CU
12/11	-11,-12	05,05	09,10	.60	.00	1	.1	CU
13/11	-03,-13	04,05	09,13	1.40	.00	1	.2	CU
14/11	-13,-13	05,05	12,12	2.10	.00	1	.1	CU
26/11	-09,-17	05,06	09,12	1.80	1.30*	14	2.4	CU
27/11	-10,-15	04,05	08,13	3.00	1.30*	48	6.1	CU
07/12	-09,-14	05,05	07,11	1.10	.50*	9	1.3	CU
11/12	-12,-17	05,06	10,12	1.50	.80*	8	1.5	CU
12/12	-04,-08	05,05	11,15	2.50	1.10*	5	.7	CU
13/12	-11,-25	05,08	07,19	3.00	.90	20	3.4	CU
14/12	-07,-19	04,07	07,27	2.40	.89	8	1.3	CU
17/12	-12,-16	06,07	09,14	1.90	.90	16	2.5	CU
18/12	-10,-17	05,06	07,14	2.30	1.30*	30	4.9	CU
19/12	12,-15	06,06	06,15	2.30	1.50*	26	3.9	CU
20/12	-12,-18	06,07	12,16	2.50	1.30*	14	2.3	CU
21/12	-08,-23	06,08	09,26	2.70	.70	18	2.8	CU

Table 1.1 (continued)

Date	Temp Range °C	Alt Range kft.	MVD Range micron	Max. LWC J.W. grams/m^3	Max. LWC FSSP grams/m^3	Distance/Time in clouds km	Distance/Time in clouds min	Type of Clouds
				1985-WINTER				
02/01	-03,-08	04,05	04,24	2.50	.40	33	5.1	CU
03/01	-14,-19	06,07	08,21	2.50	.50	19	3.0	CU
04/01	-10,-16	06,06	07,30	1.20	.30	10	1.5	CU
07/01	-10,-16	05,05	07,11	1.60	.40*	15	2.2	CU
10/01	-10,-19	05,06	05,22	2.60	.50*	32	4.9	CU
11/01	-11,-16	05,06	07,10	2.30	.06*	18	3.0	CU
17/01	02,-10	04,05	07,18	3.10	.90*	16	2.5	CU
18/01	-12,-15	07,07	10,26	3.10	1.50*	31	5.1	CU
21/01	-01,-14	06,07	08,12	2.90	.70*	18	2.6	CU
22/01	-10,-12	06,06	09,12	3.00	.80*	27	4.0	CU
24/01	-09,-12	06,06	09,12	2.50	.70*	11	1.7	CU
28/01	-10,-12	06,06	10,25	2.20	.60*	21	3.0	CU
29/01	-10,-15	06,07	07,12	2.70	.90	27	4.2	CU
30/01	-11,-14	06,07	03,07	5.00	.10	22	3.5	CU
05/02	-10,-19	07,08	04,08	2.20	.20*	29	3.3	CU
11/02	-01,-08	05,06	10,15	2.80	2.30*	13	2.0	CU
13/02	-02,-11	04,05	04,18	2.30	2.10*	33	5.4	CU
14/02	08,-05	03,04	08,13	1.20	1.30*	9	1.5	CU
15/02	-12,-18	05,06	06,21	3.00	2.30*	82	8.5	CU
18/02	-09,-16	06,07	06,16	2.60	1.70*	42	6.1	CU
21/02	-10,-21	06,07	04,15	2.50	2.30	33	5.3	CU
22/02	-11,-14	06,06	09,13	2.30	1.50*	10	1.4	CU
25/02	-09,-12	06,06	08,13	2.40	1.50*	30	4.8	CU
26/02	-11,-15	06,07	07,14	2.70	2.50*	19	3.1	CU
27/02	-10,-14	06,06	09,16	2.70	2.00*	59	9.0	CU
28/02	-01,-14	04,06	06,15	2.30	2.60*	21	3.5	CU
01/03	-09,-10	05,05	11,16	2.50	1.90*	5	.8	CU
07/03	-12,-13	05,05	06,13	2.10	1.30*	41	6.7	CU
08/03	-11,-12	05,05	08,13	1.80	1.30	12	1.9	CU
11/03	-11,-13	05,05	11,15	2.50	1.70	6	1.0	CU
12/03	-08,-11	05,05	11,13	2.20	1.50*	18	2.8	CU
13/03	01,-04	04,05	05,13	1.50	1.30*	22	3.8	CU
18/03	-12,-15	05,05	05,15	2.90	2.20	13	2.1	CU
26/03	-03,-16	04,05	08,15	2.00	1.50*	16	2.4	CU
				DATA COLLECTED BY THE LABORATOIRE ASSOCIE DE METEOROLOGIE PHYSIQUE				
				All Flights over Southern France-1984				
05/06	-04,-21	02,08	07,35	2.58	4.59*	82	15.0	CU
06/06	-04,-21	02,08	08,35	1.89	1.80	147	26.7	CU
07/06	-00,-27	02,08	08,36	1.95	2.33*	74	12.9	CU

Table 1.1 (continued)

Date	Temp Range °C	Alt Range kft.	MVD Range micron	Max. LWC J.W. grams/m^3	Max. LWC FSSP grams/m^3	Distance/Time in clouds km	Distance/Time in clouds min	Type of Clouds
19/06	-06,-21	02,07	07,36	0.00	1.07	119	20.6	CU
26/06	-07,-13	02,04	07,34	1.21	1.61	169	26.8	CU
27/06	-00,-24	05,07	07,38	1.44	1.09*	23	3.8	CU
28/06	-05,-18	04,08	08,35	1.70	2.76	115	20.0	CU
01/07	-09,-23	06,08	08,32	1.40	1.64	85	13.2	AS
02/07	-05,-07	04,06	05,16	.76	.44*	20	3.2	ST

DATA FROM THE UNIVERSITY OF CAMBRIDGE, ENGLAND

This data is different than flight data in that it is data from a tower which is enveloped in clouds for long periods of time. Thus there is no range in altitude or distance of penetration. The following is five days of cloud data and two days of ground fog data.

			Cloud Data	
			1984	
06/04	01/-02	06,24	1.43	97
07/04	00/-01	05,21	.96	115
12/04	01/-02	13,16	1.33	130
			1985	
11/08	01/-02	16,17	.60	125
12/12	00/-01	11/12	.51	11
			1982 Ground Fog Data	
24/03	00/-01	10/12	.57	108
			1983 Ground Fog Data	
27/10	00/-01	10/12	.85	123

TABLE 1.2

SUMMARY OF GERMAN DATA

GERMANY
1983/1984

Date	Alt. km	Temp. °C	LWC gm/m^3	MVD micron	Dist. km	Time min	Cloud
9/1	02	-14	.18	-	297	75	ST, SC
16/1	03	-12	.17	23	233	58	CU
17/1	02	-03	.36	27	600	149	AS, CU, NS
18/1	02	-13	.37	21	440	108	SC, ST
25/1	02	-12	.47	15	559	137	AC, AS
2/3	02	-06	.14	13	197	49	AC, AS
8/3	02	-12	.09	-	201	50	AC, AS
9/3	02	-13	.25	-	318	78	AC, AS
27/3	03	-10	.19	15	583	145	AC, AS
28/3	03	-06	.18	25	257	64	AS
29/3	03	-09	.17	-	297	74	AS
3/4	02	-11	.37	17	688	170	SC, AC

1984/1985

Date	Alt. km	Temp. °C	LWC gm/m^3	MVD micron	Dist. km	Time min	Cloud
10/12	03	-03	.09	33	257	63	ST
11/12	03	-03	.10	25	359	88	SC
25/01	02	-10	.24	19	478	119	AC
30/01	03	-05	.13	36	352	89	AC, AS
06/02	02	-04	.36	-	276	71	AC, AS
07/02	02	-05	.79	21	663	170	NS, AC
11/03	02	-11	.32	15	633	165	SC, AC
12/03	01	-07	.43	21	405	104	ST, AS
26/04	01	-03	.30	-	299	79	ST, AS
29/04	02	-10	.44	15	363	93	AC

1985/1986

Date	Alt. km	Temp. °C	LWC gm/m^3	MVD micron	Dist. km	Time min	Cloud
05/03	03	-04	.08	27	397	92	ST
07/03	02	-05	.21	27	487	123	ST
13/03	01	-04	.49	23	290	78	ST
21/03	02	-11	.15	19	367	90	AS, AC
24/03	03	-03	.19	21	290	70	AC
03/04	03	-06	.07	13	493	111	AS, AC
04/04	02	-05	.30	17	822	214	SC

France and England. The data received was normally collected at one hertz intervals and included altitude, ambient temperature, liquid water content from two instruments, median volume diameter, and cloud type.

In some cases (particularly the Canadian), the incoming data included much time during which the aircraft was not flying in a cloud. Hence the incoming data was filtered through a computer program that eliminated these data and also averaged the one hertz data over one minute. This data was then subjected to visual scrutiny for obvious instrument error or other types of malfunctions.

Finally, this averaged data was further summarized by determining given values for each day of flight. These are the values that appear in Table 1.1:

1 Date
2 Temperature range, °C
3 Altitude range, kft
4 Median volume diameter range, micrometers
5 Maximum Liquid Water Content from both the LWC and FSSP. The asterik signifies that the maximum reading from both instruments occurred at the same time.
6 Kilometer and minutes in clouds
7 Type of clouds.

Table 1.1 is intended to give the reader a sense of the quality and quantity of data received.

1.2 NON-MAGNETIC TAPE DATA

Unfortunately, the data received from Germany was not one hertz data. Also, it was received on hardcopy printout in tabular form and all attempts to acquire the original aircraft data failed. However, a summary of the data received from Germany is shown in Table 1.2.

SECTION 2
GEOGRAPHICAL OCCURRENCE OF SEVERE ICING

This section discusses the world-wide occurrence of "severe" icing. Later in the section a workable definition of severe icing will be developed in terms of characterizing the world-wide icing environment. The occurrence of severe icing is much more widespread than is shown by the existing or future FAA icing data base. Therefore, there is no guarantee that a characterization of the icing atmosphere based on the available data is either representative or conservative. A first step to remedy this shortcoming is to identify the extent of severe icing. Unfortunately this is not currently feasible on a global scale, however, it is possible for a large part of the northern hemisphere primarily north of 20 to 30° north latitude. After identification, the areas of severe icing for which there are measurements can be compared to those without measurements. From this comparison two conclusions can be drawn. One, the extent of severe icing without measurements is much greater than that with measurements. Two, it is likely that the most severe icing environment lies within the former areas. These conclusions will be expanded upon with more evidential support later.

2.1 DEFINITION OF "SEVERE" ICING

It is necessary to define "severe" icing. A few philosophical comments are apropo. The definition has to be meaningful in aviation terms (i.e., one would expect most aircraft to have difficulty in the event of a "severe" icing encounter); however, the definition has to be simple enough to be applicable and has to reflect existing technology with regard to icing parameters (see Section 3.1). One difficulty is that aviation and meteorology use different parameters and units for describing icing, many of which are infrequently measured. But the core of the problem is that the capability to predict the amount and nature of ice accretion given the simple problem of constant ambient conditions has not yet been acceptably established. And finally the realistic

problem of variable cloud conditions has not been satisfactorily addressed. Consider previous definitions of severe icing.

The first consideration concerns temperature. Obviously, temperature must be below 0°C for freezing to occur. Depending on the type of aircraft and its operation, however, the outside temperature must be several degrees below freezing for icing to occur. Nonetheless it is not feasible to account for all the possible combinations of aircraft and usage so we shall simply adhere to the assumption that the temperature must be below 0°C for ice to form. Additionally, we assume that no ice will form for temperature below -40°C as no liquid water is expected at this temperature and lower temperatures.

The second consideration involves the amount of cloud water or liquid water content (LWC). Generally, other things being equal, a higher LWC implies greater ice accretion. The nature of the ice accretion depends on the temperature, but as previously mentioned is not yet acceptably predictable for all temperatures. Therefore, one cannot now formulate a severe icing definition that considers LWC as a function of temperature so that, for example, a LWC of .5 gm/m^3 at -5°C would be considered as severe as a LWC of 1 gm/m^3 at a temperature of -15°C. In the future, such a definition would be desirable and would certainly make the definition more realistic in terms of the severity an aircraft would actually experience. The popular LWC value for severe icing seems to be 1 gram of LWC per 1 meter volume of air with no consideration of temperature.

The medium volume diameter (MVD) drop size is another factor that influences the severity of icing. Larger drops having greater inertia are not only more likely to strike an aircraft increasing the resulting ice accretion but also strike the aircraft on unprotected areas. Thus, as far as aircraft are concerned, the MVD is very important to severe icing. Unfortunately, it is not possible to delineate the global icing environment in terms of the MVD because as discussed in Section 3.1 there are a plethora of environmental factors which influence the drop size distribution

and hence the MVD. In order to specify the MVD for given environmental conditions, it is at least necessary to have a priori knowledge of these environmental factors. Because it is currently impossible to do this we are forced to ignore the important MVD value in our derivation of a "severe" icing definition.

A final word on horizontal and vertical extent of severe icing is also in order. Obviously, moderate LWC's below 1 gm/m^3 extending horizontally for great distances and of considerable vertical extent are more serious to an aircraft than are spatially limited occurrences of higher LWC's. Isolated instances of extremely high LWC such as occurring in cumulonimbus clouds are readily avoided by an aircraft while horizontally extensive layers of moderate LWC are not easily avoided. This is why a severe icing definition of LWC > 1 gm/m^3 for $-40°C < T < 0°C$ is sensible since it applies to the extreme values of layer cloud liquid water.

2.2 SEVERE ICING ENVIRONMENT

2.2.1 Antecedent Studies

The first task in characterizing the global severe icing environment is to identify regions where severe icing occurs frequently. This task though is complicated by a lack of directly measured data for regions where the most frequent severe icing conditions are expected (i.e., oceanic areas to the east of continents). Therefore, it is necessary to resort to indirect methods such as numerical calculation of LWC. Numerical model results can be corroborated where direct or indirect measurements are available. Before considering numerical model results it is useful to briefly review earlier work.

During the 1950's, the Air Weather Service flew a number of icing reconnaissance flights over the North Pacific and North Atlantic Oceans. The reconnaissance aircraft flew at the same levels (700 mb and 500 mb) on the same routes everyday. Therefore, it was possible to statistically analyze the results (Appleman, 1959) in the form of a conditional probability of

aircraft icing given cloud amounts > 6/10 as a function of temperature and altitude.

Katz (1967) used these results in addition to temperature and cloud data to calculate the probability of icing in the intervals 0 to 5,000 feet, 5,000 to 10,000 feet, 10,000 to 15,000 feet, and 15,000 to 20,000 feet by season over the northern hemisphere. He assumed that the mean cloud amount at an altitude is equal to the probability of cloud amounts > 6/10 at that same altitude. As a result his probability of icing is

$$P(I) = \int_{-40°C}^{-2°} F[I(T) / C > 6/10]\, P[C > 6/10]\, F(T)\, dt$$

where

$F[I(T)] / C > 6/10]$ = conditional probability density function of icing given a cloud amount 6/10 as a function of temperature,

$P[C > 6/10]$ = probability of cloud amount greater or equal to 6/10, and

$F(T)$ = probability density function of temperature.

The results of Katz's study for 0 to 5,000 feet in winter give the highest probabilities of icing occurrence over eastern Canada and southern Greenland $P > 0.15$, northern central Europe $P > 0.15$, and the western and northern Pacific $P > 0.10$. In spring the dist ibution is similar except for $P > 0.15$ over the northern Pacific. In summer and fall the probabilities are generally less except over the Bering Strait i.e., $P < 0.15$ in the fall. In general, the probabilities are less with increasing altitude with the exception of southeast Asia during the summer monsoon months, at 15,000 to 20,000 feet $P > 0.10$. For our purposes, the Katz study has two major deficiencies. One, the study is based on limited data and therefore may not be truly representative for those areas without much data (i.e., no

rawinsondes), and two, Katz doesn't really consider "severe" icing.

In Heath (1972), the frequency of icing occurrence was calculated for the northern hemisphere. Temperature and dew-point data for 380 radiosonde stations were analyzed for frequency of occurrence of temperature/dew-point temperature differences when the temperature is below 0°C for the 1,000 mb, 850 mb, 700 mb, and 500 mb pressure surfaces. These differences were correlated to a probability of icing based on the results from the Air Weather Service reconnaissance flights. The final icing probability was then an integral over temperature of the probability density function of temperature/dew-point temperature difference times the probability of icing given those conditions. Heath's results show that a high frequency of icing occurrence is expected over southeastern Canada at 850 mb $P > 0.10$, over Scandinavia and northeastern Russia $P > 0.15$, and over the northern and western Pacific $P > 0.20$ in January. Again, as for the Katz results, there is not enough data to guarantee full resolution of icing occurrence, and again severe icing is not considered. In addition, Katz and Heath somewhat differ in their results although the overall fields are similar.

Other studies have been done but are generally regional or local in nature. Roach et al. (1984) analyzed 20,000 World War II reconnaissance flights along with some recent flights in producing a supercooled cloud climatology for the northeastern Atlantic Ocean. The analysis shows that the probability of supercooled cloud with LWC ≥ 0.5 gm/m^3 exceeds 0.02 at 850 mb during winter for an area to the northwest of the British Isles and south of Iceland. Probabilities for exceeding this threshold are lower elsewhere and at all other vertical levels analyzed. The probability for exceeding 0.2 gm/m^3 at 850 mb during winter for the same area is 0.10. The latter figure is consistent with the probability of icing found by Heath and similar to the value found by Katz. We know of no similar studies for the southern hemisphere.

2.3 ETAC DATA BASE MAPS

In 1984, the United States Air Force Environmental Technical Applications Center (ETAC) compiled an extensive liquid water content (LWC) data base for the years 1977-1980. In 1986 the LWC values were calculated on the Air Weather Service (AWS) northern hemisphere IJ grid for much of the northern hemisphere (north of 30° north) and at 15 vertical levels. The approximate horizontal spacing of these grid points is 200 nautical miles; somewhat less for lower latitude grid points and somewhat more for higher latitude points. The original Smith-Feddes model (Smith 1974, Feddes 1974) described in Section 3.2 was used with archived twice daily three-dimensional nephanalysis (3DNEPH) and AWS analyses for the above mentioned 4-year period. 3DNEPH analyses were produced at a horizontal resolution of 25 nautical miles so that an LWC grid point is representative of 64 3DNEPH values. As a result, approximately 240 LWC values were generated at each vertical level at points north of 30° on the IJ grid for each month of the year. 3DNEPH analyses of tropical and southern hemisphere regions were apparently lacking therefore the LWC values for these areas could not be calculated.

The conditional probability of LWC values greater than 1 gm/m^3 with temperatures between 0°C and -40°C was calculated annually and monthly from the data base. This probability was calculated in the eight vertical layers listed below in Table 2.1 at each IJ grid point.

TABLE 2.1

SEVERE ICING PROBABILITY CALCULATION LEVELS

Layer	Altitude Range (m)
1	1 - 500
2	501 - 1000
3	1001 - 1500
4	1501 - 2000
5	2001 - 2500
6	2501 - 3000
7	3001 - 4500
8	4501 - 6000

The conditional probabilities are indicative of the frequency of occurrence of severe icing as defined in Section 2.1 However, the Smith-Feddes model probably exhibits a systematic bias for overestimating LWC values. Therefore, while the resulting probabilities of LWC greater than 1 gm/m^3 are high, the distribution of higher probabilities properly delineates the severe icing environment.

The monthly variation of the results are similar within seasons. For example, the results for December and February are quite similar to those for January and results for June and August are quite similar to those for July, etc. Thus, the months of January, April, July, and October are representative of the winter, spring, summer, and fall seasons, respectively.

Figure 2.1 shows the distribution of "severe icing" for the second layer (501-1000 m) during April. In general, probabilities for layer 1 (1-500 m) are quite low as the cloud base is frequently higher than 500 m and higher LWC values usually occur in proximity to the cloud top rather than cloud base. Higher probabilities (>10%) are limited to higher latitudes with the most extensive occurrences near and south of the Kamchatka peninsula, over eastern Siberia from Lake Baykal to Sakhalin island, north of the Yenisey in the northern Soviet Union, over the north Atlantic from Greenland to the North Sea, over Norway and Sweden, over part of central Europe, over southern Alaska, and over eastern Quebec and Labrador. Especially high probabilities are located just north and east of Norway and over the Kunlun mountain range north of Tibet. This latter feature appears in many of the icing probability charts and may be spurious.

Figure 2.2 shows the distribution for layer 4 (1501 - 2000 m) in April. In general, the probabilities are higher and the severe icing occurrence is more extensive than for layer 2. The occurrence is particularly more widespread from the Great Lakes northeastward through northern New England and Quebec. There is

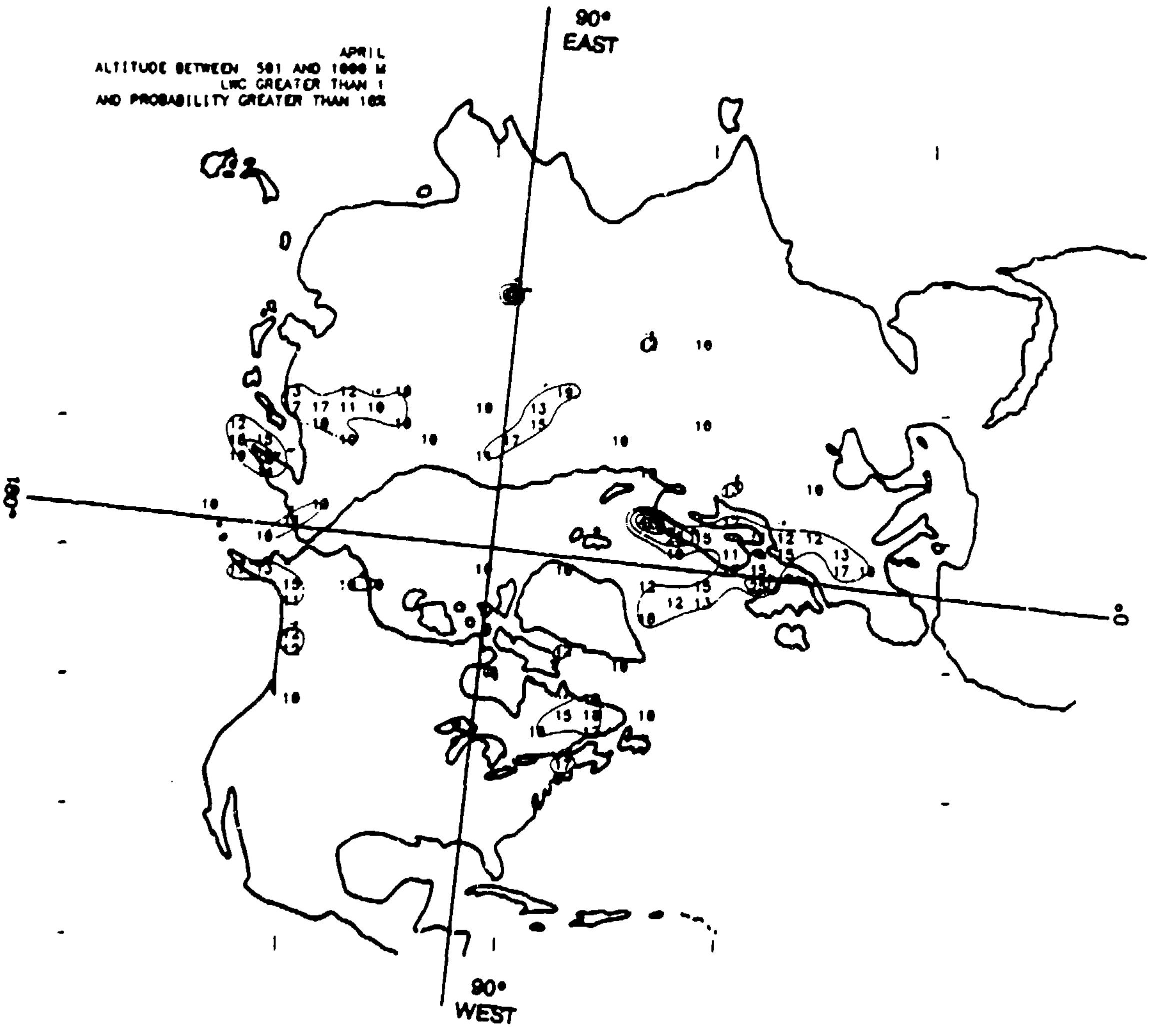

Figure 2.1 Occurrence of Supercooled Liquid Water Content Greater than $1 gm/m^3$ in April at 501-1000 meters. (Map shows only those regions where the frequency of occurrence is 10% or greater.)

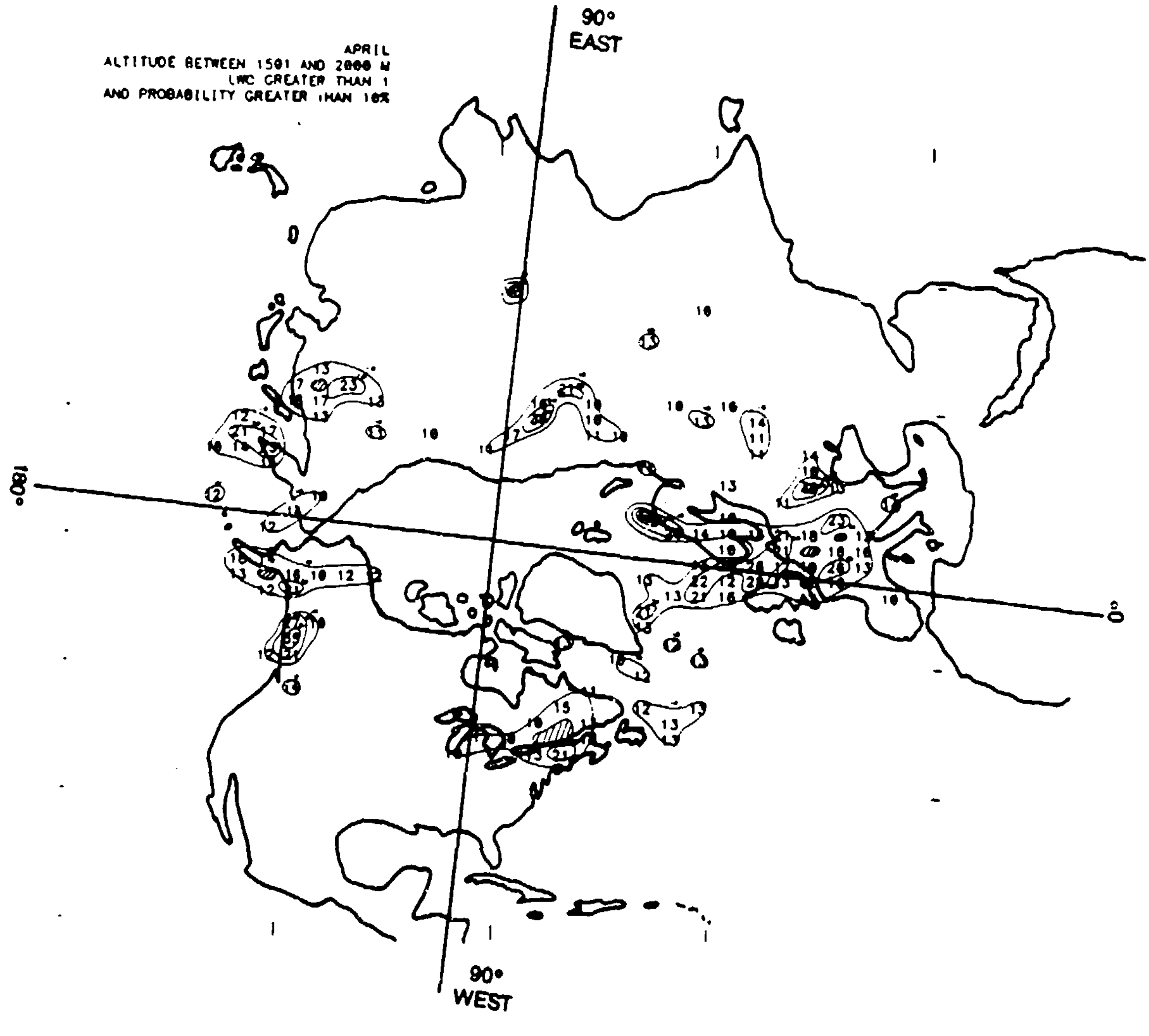

Figure 2.2 Occurrence of Supercooled Liquid Water Content Greater than 1gm/m³ in April at 1501-2000 meters. (Map shows only those regions where the frequency of occurrence is 10% or greater.)

also another prominent area located over British Columbia that does not appear for layer 2. Layers 3 and 4 distributions are quite similar.

Above 2000 m, the occurrence of severe icing is greatly diminished. Layer 6 (2501-3000 m) shown in Figure 2.3, is representative of the upper four layers. The occurrence of higher probabilities is quite spotty with only small areas in the northern Soviet Union and Norway noteworthy.

The severe icing environment is of very limited extent during the summer as shown in Figure 2.4 for the eighth layer (4501 - 6000 m). This is the only summer layer in which high icing probabilities appear. The exceptions are for the South China Sea and over the northern Bay of Bengal and over central Scandinavia. The high probabilities associated with the Asian monsoon are probably spurious as the 3DNEPH analyses in this region overestimates cloud amount (Hughes, Henderson-Sellers 1985).

The severe icing environment during autumn shown in Figures 2.5, 2.6, and 2.7 is located even more northward than its spring counterpart. The most extensive occurrences shown in Figure 2.5 for the 501 - 1000 m layer are located over Alaska, northern Quebec and Baffin Island, northern Norway, and the northern Soviet Union. The distribution for the fourth layer (1501 - 2000 m) shown in Figure 2.6 is quite similar, however, the severe icing environment is more extensive over the north Atlantic from Greenland to Norway and over eastern Siberia and the Kamchatka peninsula. Layers 3 and 4 distributions are again quite similar. Figure 2.7 shows the distribution in layer 6 which is again quite representative of the layers above 2000 m. Higher probabilities occur over Alaska and the northern Soviet Union.

The northern hemisphere severe icing environment is most widespread during the winter as shown in Figures 2.8, 2.9, and 2.10. Figure 2.8 shows the distribution for layer 2 (501 - 1000 m) for which there are three large areas of severe icing: the eastern Asia littoral from Japan to the Kamchatka peninsula,

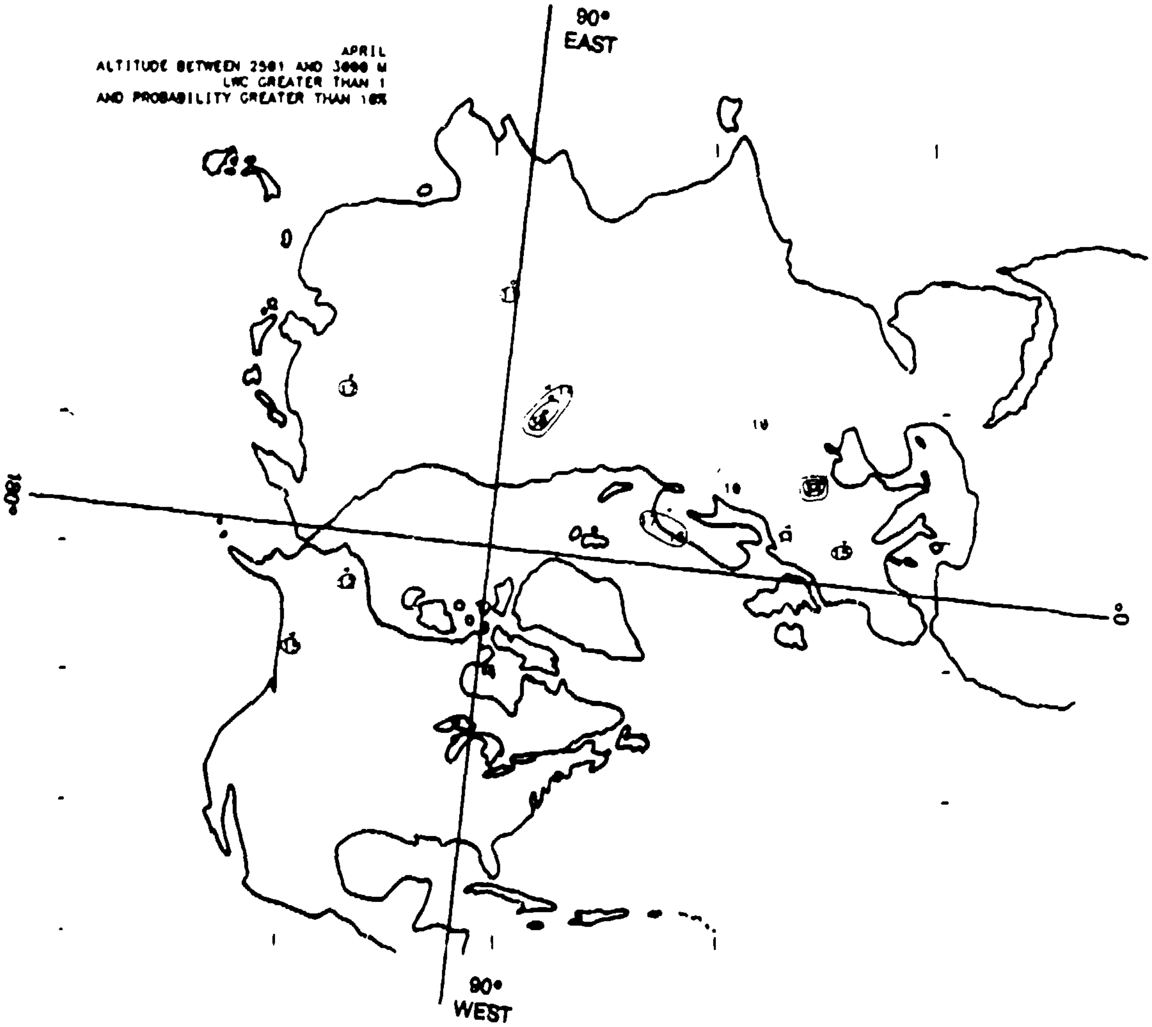

Figure 2.3 Occurrence of Supercooled Liquid Water Content Greater than 1gm/m³ in April at 2501-3000 meters. (Map shows only those regions where the frequency of occurrence is 10% or greater.)

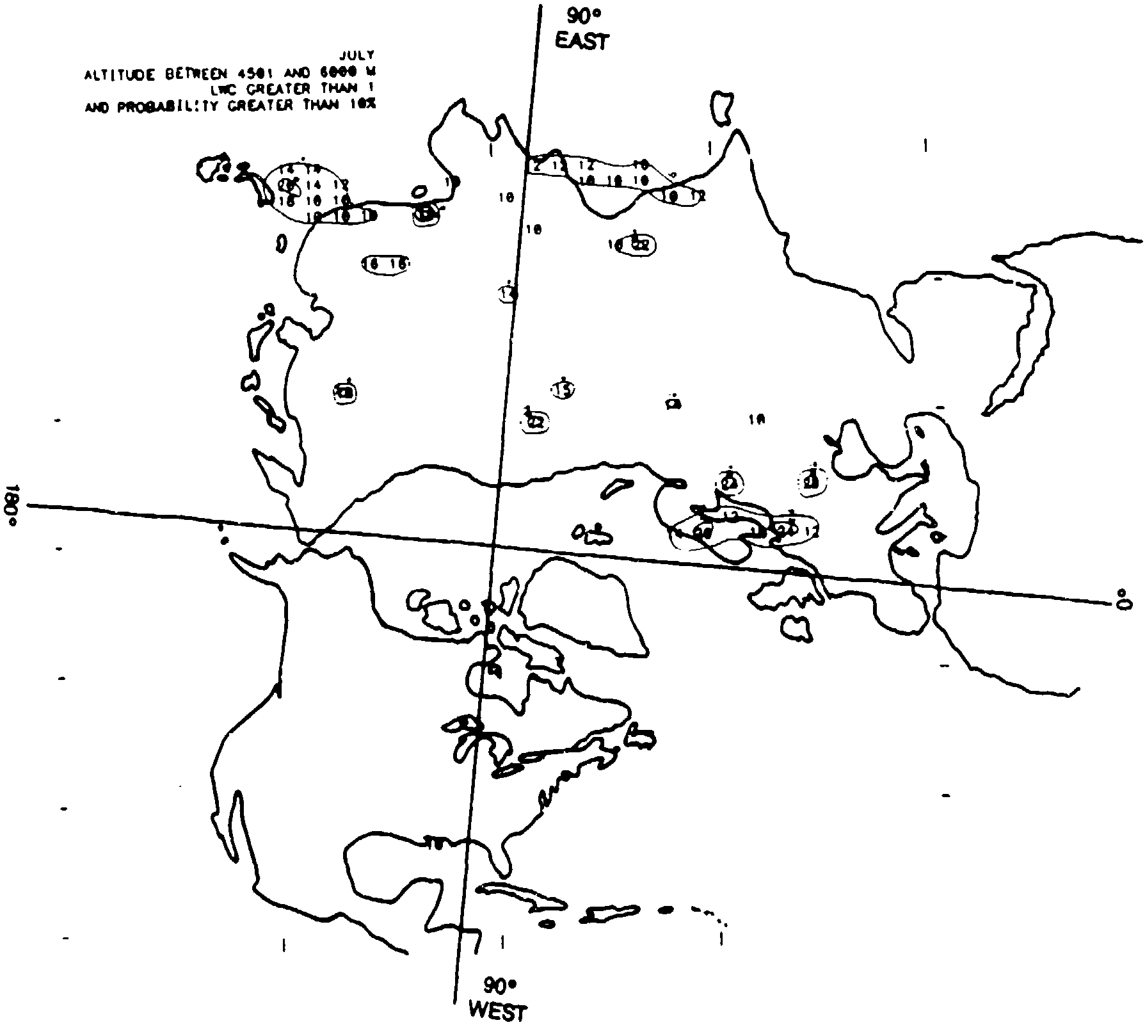

Figure 2.4 Occurrence of Supercooled Liquid Water Content Greater than 1gm/m³ in July at 4501-6000 meters. (Map shows only those regions where the frequency of occurrence is 10% or greater.)

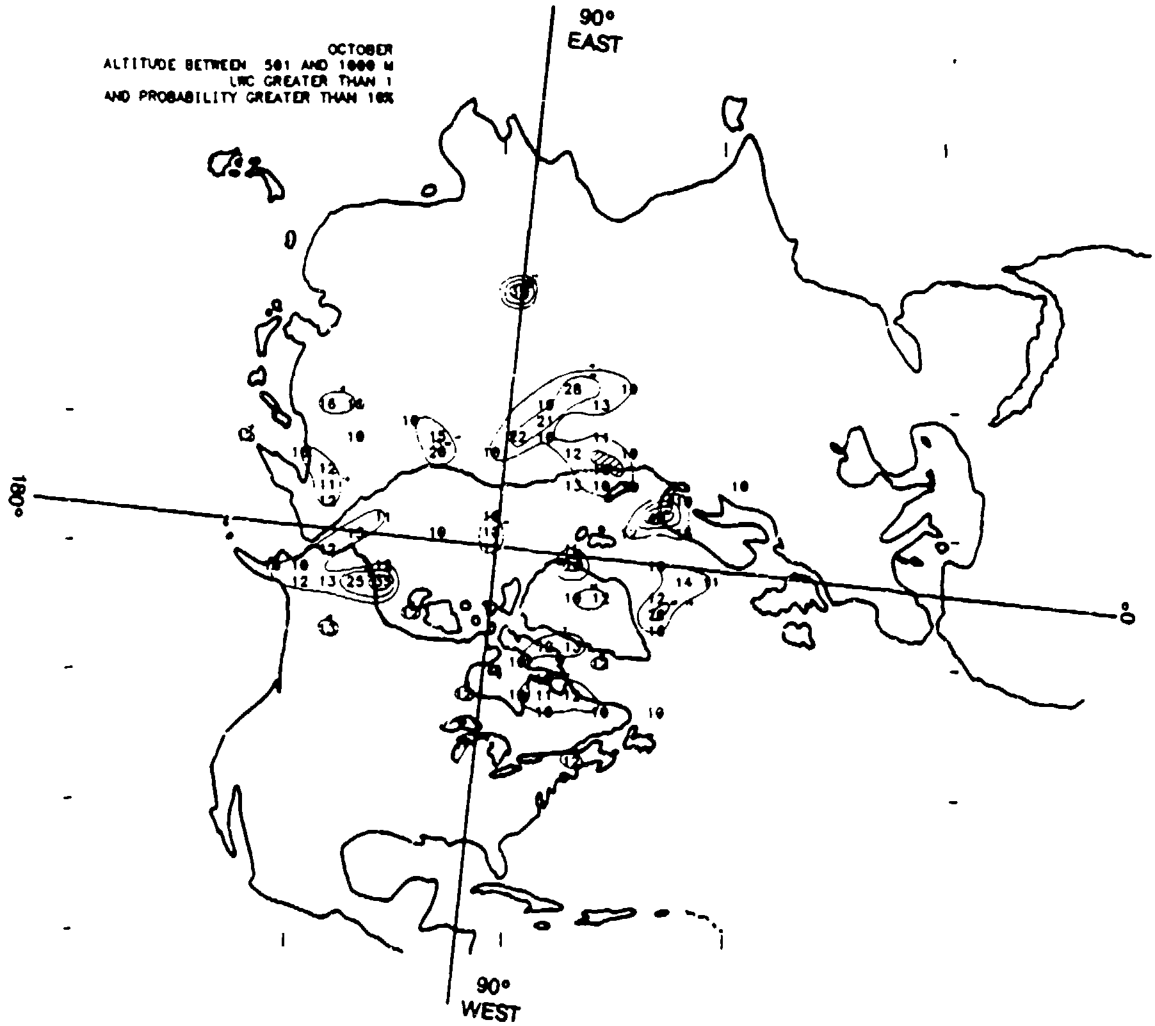

Figure 2.5 Occurrence of Supercooled Liquid Water Content Greater than 1gm/m³ in October at 501-1000 meters. (Map shows only those regions where the frequency of occurrence is 10% or greater.)

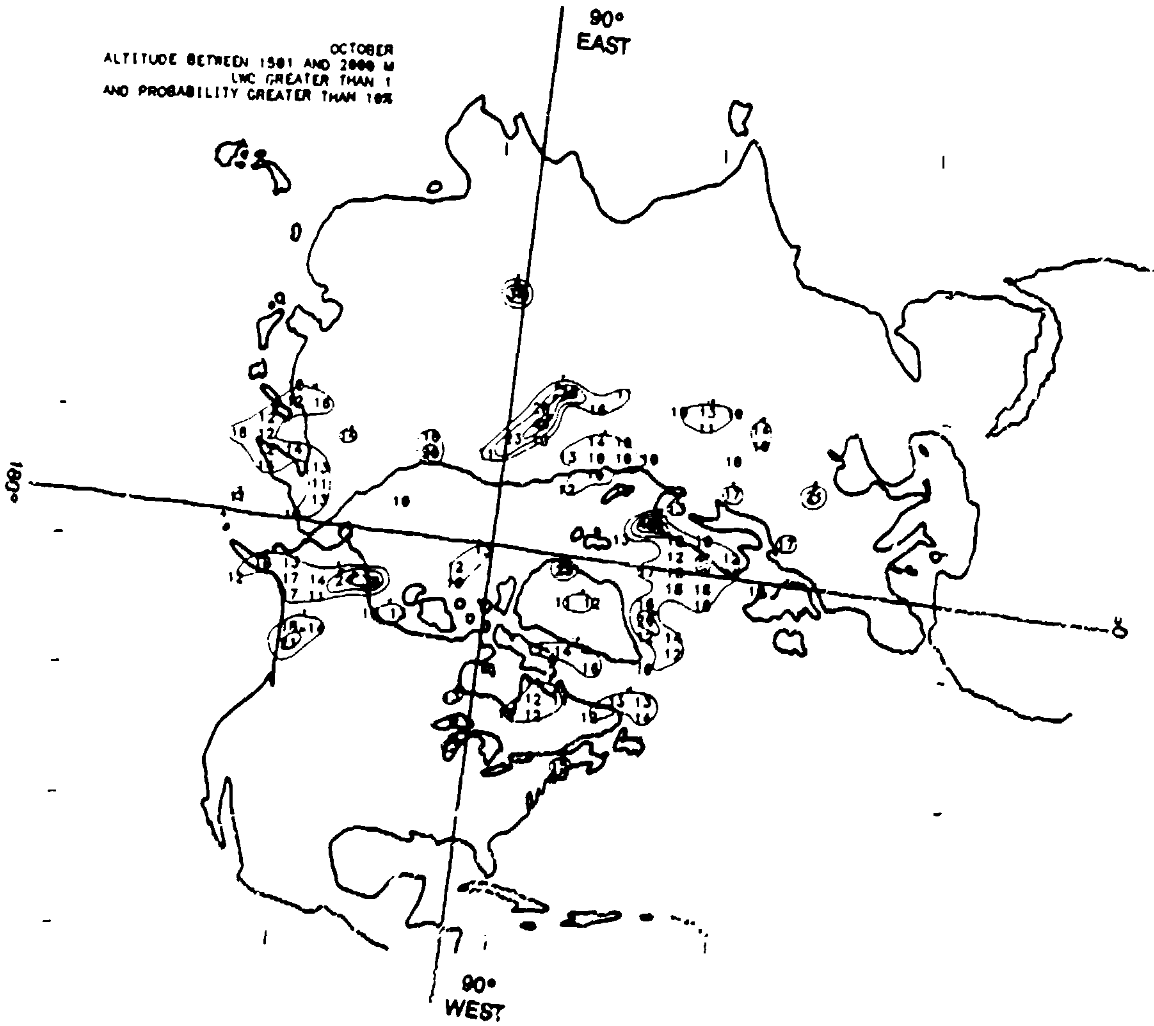

Figure 2.6 Occurrence of Supercooled Liquid Water Content Greater than 1gm/m³ in October at 1501-2000 meters. (Map shows only those regions where the frequency of occurrence is 10% or greater.)

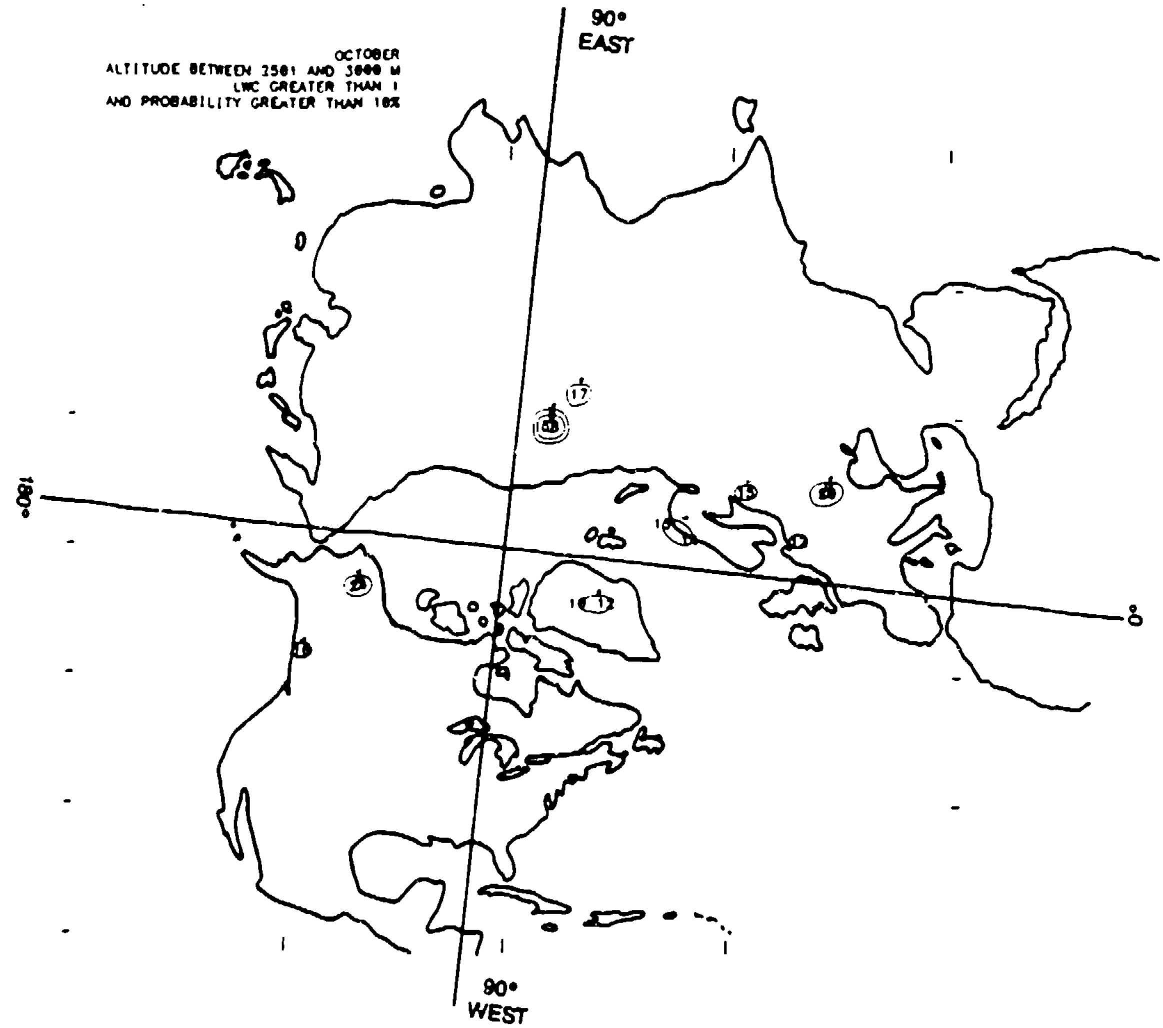

Figure 2.7 Occurrence of Supercooled Liquid Water Content Greater than 1gm/m³ in October at 2501-3000 meters. (Map shows only those regions where the frequency of occurrence is 10% or greater.)

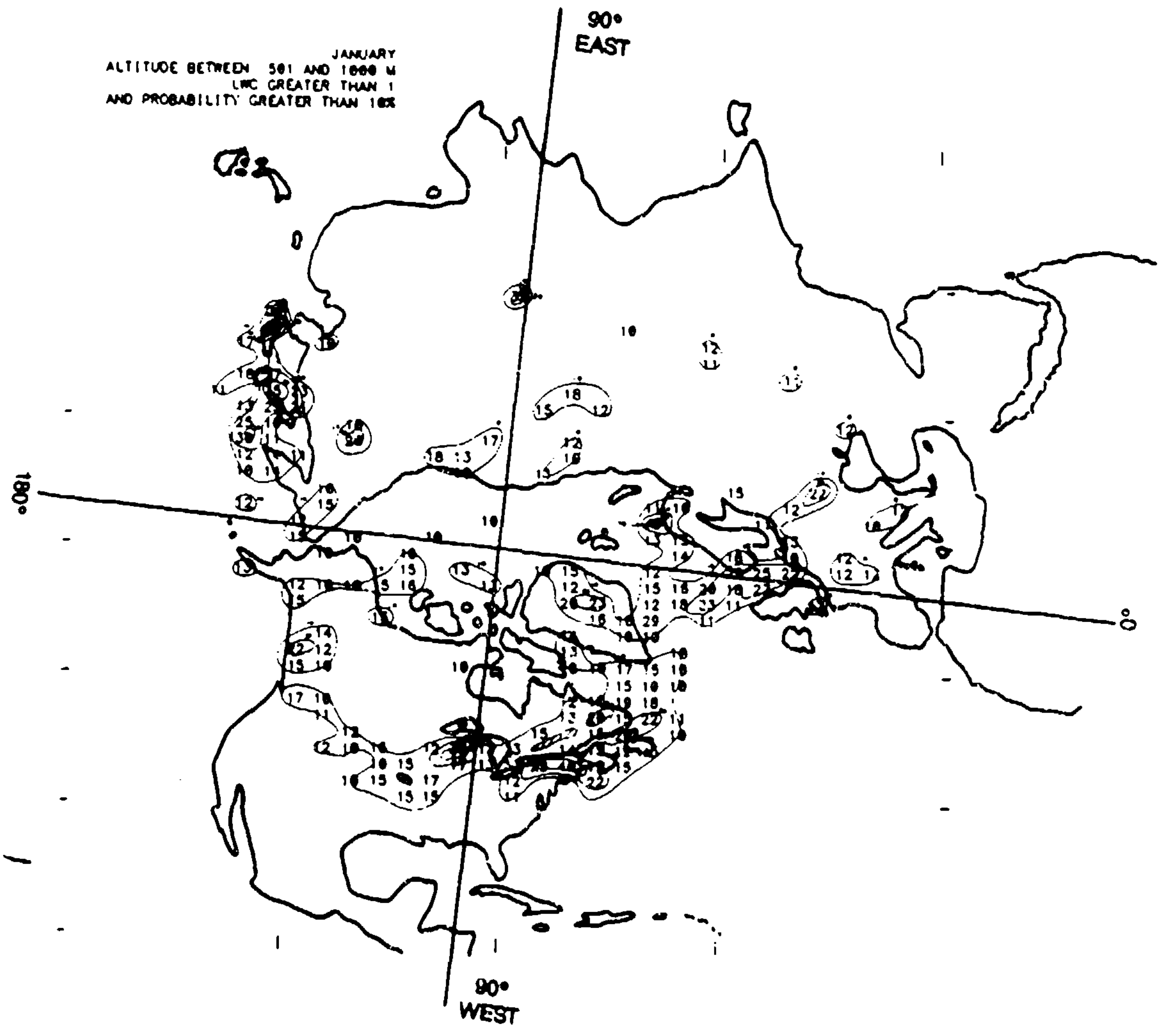

Figure 2.8 Occurrence of Supercooled Liquid Water Content Greater than 1gm/m³ in January at 501-1000 meters. (Map shows only those regions where the frequency of occurrence is 10% or greater.)

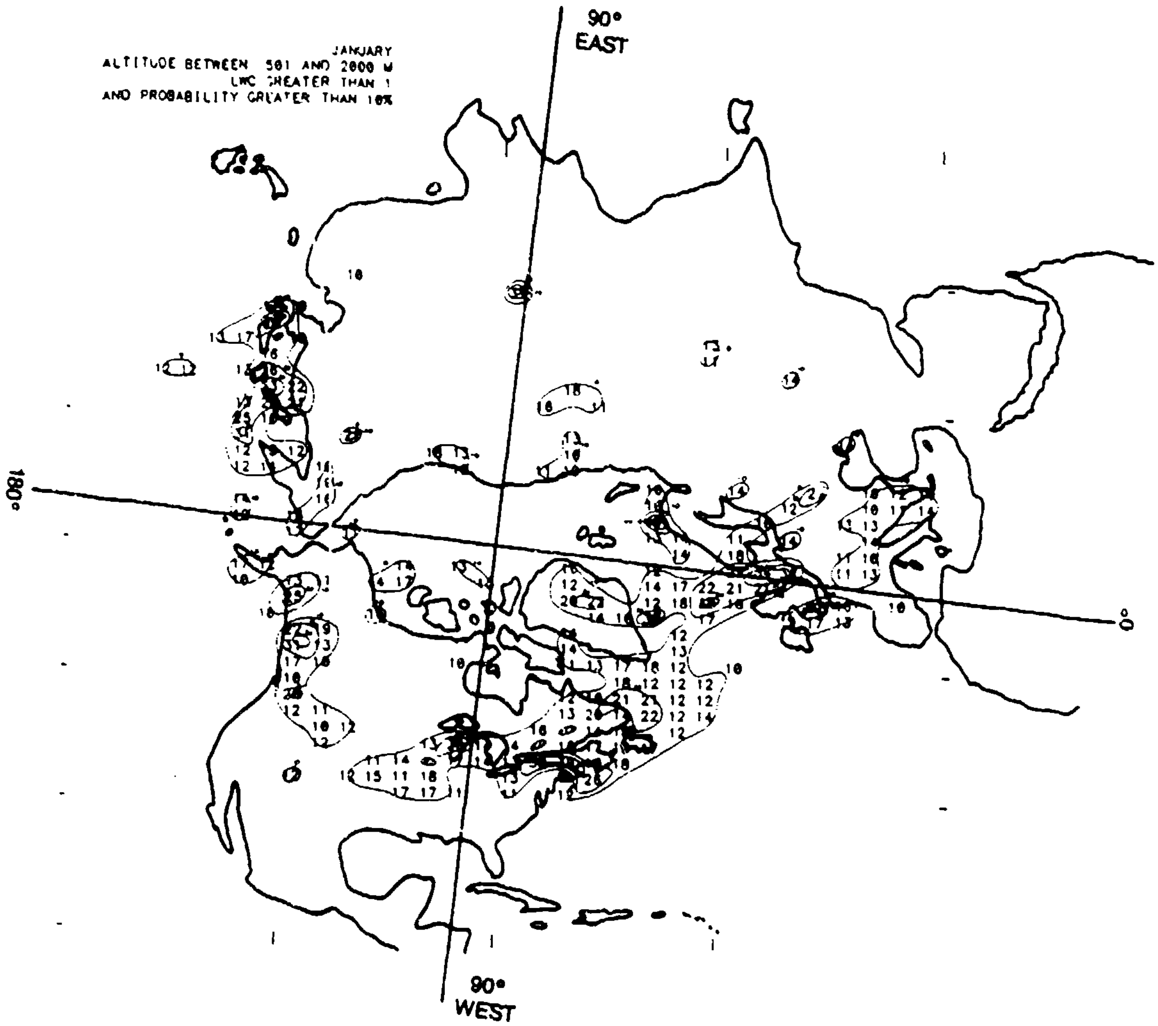

Figure 2.9 Occurrence of Supercooled Liquid Water Content Greater than $1 gm/m^3$ in January at 1501-2000 meters. (Map shows only those regions where the frequency of occurrence is 10% or greater.)

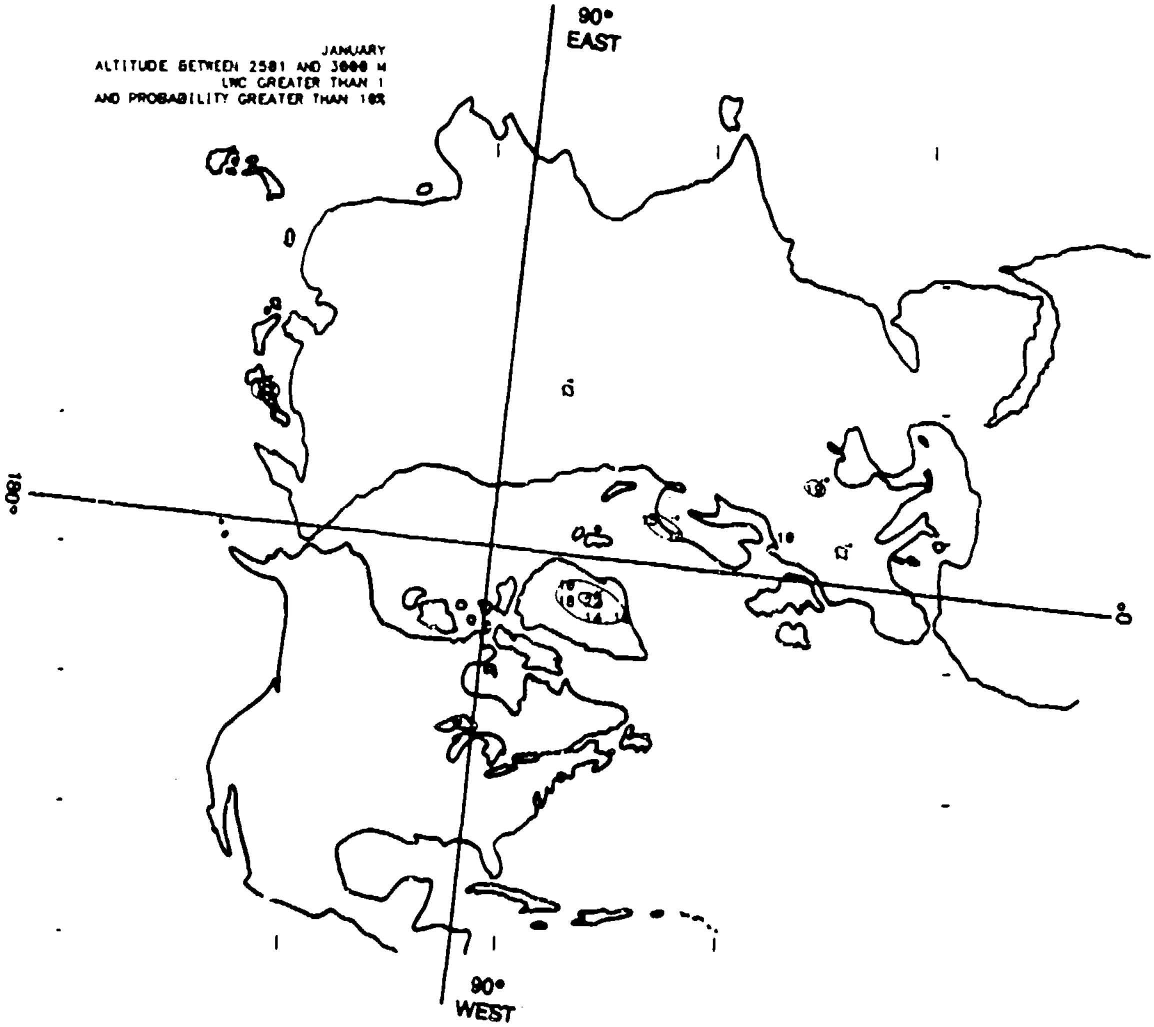

Figure 2.10 Occurrence of Supercooled Liquid Water Content Greater than 1gm/m³ in January at 2501-3000 meters. (Map shows only those regions where the frequency of occurrence is 10% or greater.)

across the central United States and eastern Canada to the western north Atlantic, and the eastern north Atlantic from Greenland to Scandinavia and the North Sea. Smaller areas are located over the northern Soviet Union, Alaska, and western Canada. The winter severe icing environment seems to coincide with the northern hemisphere cyclone tracks and is highly correlated with the higher probabilities of cloud as revealed the Hughes and Henderson-Sellars cloud climatologies.

It might be surprising that the severe icing environment is of such limited extent over most of the Soviet Union. However, extensive moisture sources are located far from the Soviet Union and the low temperatures there additionally limit moisture. This situation is apparently repeated for much of western and central Canada where severe icing probabilities are low.

The distribution for layer 4 (1501 - 2000 m) shown in Figure 2.9 is similar to that of Figure 2.8 and similar to that for layer 3 as well. Overall probabilities are higher and the severe icing environment over central and southeastern Europe is considerably more extensive. Some of these latter locations have altitudes of 1000 m or greater so that layer 4 may be indicative of conditions not far above cloud base for this region.

Finally, Figure 2.10 shows the winter distribution for layer 6 (2501 - 3000 m). Again this layer is representative of the upper 4 layers. Severe icing is limited to eastern Greenland, the northeastern Norway coast and a few spots in Europe and Asia. As before, the probability of severe icing occurrence decreases with increasing altitude so that the probability is virtually nil for layer eight.

As mentioned before, the frequencies of severe icing occurrences calculated using the ETAC LWC data base seem high and this is attributed to use of the original Smith-Feddes model. Nonetheless, the distribution of severe icing especially for winter coincides with high frequency of cloud occurrence as revealed in the Hughes and Henderson-Sellars cloud climatology. We believe that in spite of the caveats above, the severe icing

climatology as described here has validity in as far as the distribution of severe icing is concerned. Thus, we can assess how representative are the existing FAA/NRL icing data base and foreign data additions thereto are of the northern hemisphere severe icing environment.

2.4 AREAS OF THE NORTHERN HEMISPHERE SEVERE ICING ENVIRONMENT WITH LITTLE OR NO DATA COVERAGE

Figure 2.11 shows the locations of data collection for the current FAA/NRL icing data base and the foreign data collected under the current effort. The data has been mainly collected in Europe and North America but also includes data collected in South Africa. Extensive data collection over Lake Michigan, Nova Scotia and the Syracuse, New York area seem appropriate as the frequency of severe icing is relatively high for these locations. On the other hand, the highest probabilities of severe icing are located over Lake Superior, the Saint Lawrence river valley, British Columbia, the North Sea, and in proximity to the Japanese and Sakhalin islands. Data for these particular locations are few or nil. Thus, there is the vexing question as to whether an extreme value analysis of all existing data might inadequately portray severe icing. It is obviously impossible to make measurements at <u>all</u> locations where the maps in this section suggest a high probability of LWC. But the maps do suggest that additional data collection efforts for Lake Superior, the Saint Lawrence river valley, the North Atlantic and North Sea, and the Asian littoral would probably yield important information. Because of the high cost of aircraft measurements the alternate data development scheme discussed in Section 3 in conjunction with RTNEPH and northern hemisphere analysis fields should be implemented. In addition, satellite borne and ground-based microwave sounders could prove useful in calibrating the Smith-Feddes model.

It is also possible to follow Jeck's (1983) suggestion of deciding if there is sufficient data by examining the maximum LWC measured for a particular weather condition and then letting that guide the answer to the question "How much data is enough?"

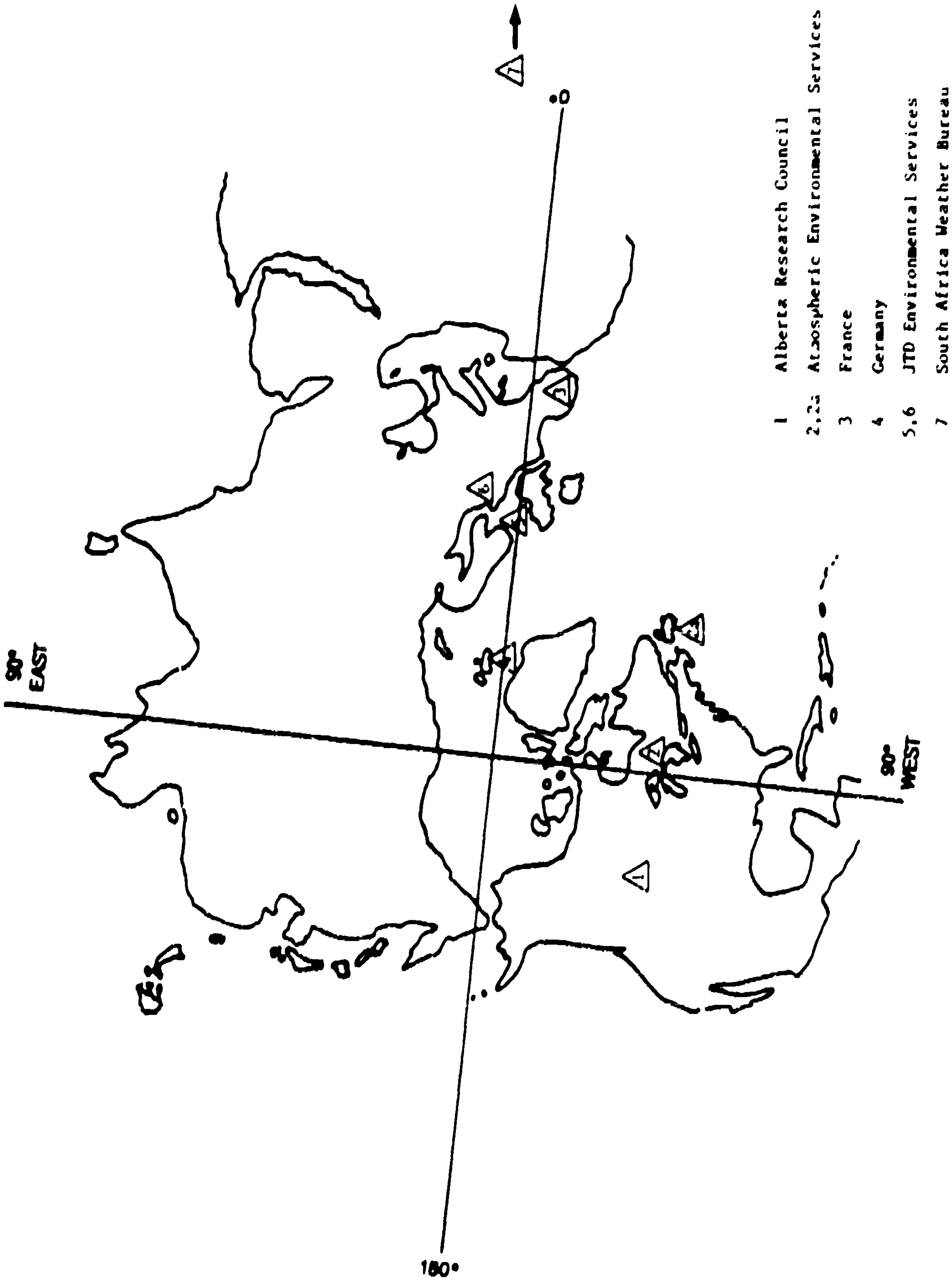

Figure 2.11 Worldwide Icing Data Collection Locations.

This is at present an impossible question to answer for the severe icing areas with no measurements since there is no maximum LWC to guide the answer. The modified updated Smith-Feddes model could help answer such a question by predicting the highest conceivable LWC. A principle difference between the foreign data and the existing data base are the high LWC's measured in South African convective clouds and the frequent occurrence of LWC > 1 gm/m^3 in some areas. The maximum appears to be 3.0 gm/m^3 with two questionable values of 5.2 gm/m^3. Similar values have been reported by the Canadians. According to the Jeck criterion for data miles:

$$M = b(LWC_{MAX})$$

where

$$b = 500 \text{ nmi/gm}^2$$

A LWC_{MAX} of 3.0 gm/m^3 translates to 1,500 nmi of data collection. Obviously that amount of data collection in deep convective clouds is expensive. The alternate data development discussed in Section 3 is perhaps more realistic (and certainly less expensive) especially for deep convective clouds. At present it is impossible to assess the amount of data collected for the various weather types mentioned by Jeck in his Table B-1 (1983). It seems probable, though, that all the weather types Jeck indicates as deficient in measurement will continue to remain so even with the newly collected data. The difficulty of remedying this deficiency is acute for these weather conditions as they are localized and changeable and thus hard to encounter. Thus the alternate data development method in the following section is an attractive means for establishing not only how much data is needed but also to extend the validity of limited measurements to satisfy these data requirements.

SECTION 3
ALTERNATE DATA DEVELOPMENT SCHEME

Current aircraft icing research is concerned with ice protection systems that are energy efficient and the needs of relaxing the certification standards, an improved characterization of the worldwide icing environment, and improved forecasting of icing conditions is required. The worldwide characterization currently consists of retrieval of data in which the icing parameters have been measured in addition to other information such as type of cloud, horizontal or vertical extent of clouds, and synoptic weather conditions. As discussed in Section 2, the parameter variation and especially geographical coverage of these measurements is insufficient to guarantee that the resulting data base is at least conservative. To guarantee this and to increase the geographical validity either additional flight data surveys or an alternate means for satisfying the data requirements are necessary.

One of the issues of the original contract was to determined if there was a need for further icing data measurements. The maps in Section 2 show that there are extensive geographical areas where severe icing is expected and for which there are few or no measurements. In addition, following the lead of Jeck (1983) certain types of meteorological conditions such as warm fronts, occluded fronts, and lake effect clouds are insufficiently represented by the data base. Thus, a need to obtain additional data to extend the data base's geographical and weather condition validity seems justified. The FAA anticipated this situation by stipulating that if additional data is required, an alternate data development scheme be formulated to reduce or negate the reliance on dedicated and costly flight surveys. The University of Dayton initiated a review of candidates for the alternate data development scheme. The results of this review are included in Sections 3.2 and 3.3.

Based on this review, the updated Smith-Feddes model (SFM) was selected as being the best candidate for an alternate data

development scheme based on a validation using the present data base of LWC and MVD values. Section 3.4 presents the results of the validation. Finally Section 3.5 presents two strategies by which a corrected SFM can satisfy the requirements of an alternate data development thus negating or certainly reducing the need for a number of costly flight surveys.

3.1 THE ICING PARAMETERS

Aircraft icing occurs when an aircraft encounters supercooled liquid water. This most frequently occurs in clouds but can also occur for the extremely dangerous situations of freezing drizzle or rain. In either case the supercooled liquids freeze upon impacting the aircraft and the resulting accretion can seriously degrade the aircraft aerodynamic performance, impair the operation of aircraft instruments, and reduce the aircraft's engine performance. The amount of performance degradation is dependent both upon the type of aircraft and environmental conditions. For a given aircraft three critical environmental parameters have been identified (Pass, 1984): air temperature (T), liquid water content (LWC), and drop size distribution (DS). In addition, it is necessary to know the cloud water phase, P_h, because relatively large areas of cloud may be glaciated presenting a benign icing environment.

Temperature is important because the type of ice accretion changes dramatically between temperatures near freezing and those considerably below freezing. At temperatures near freezing the drops do not freeze instantaneously but run back slightly forming a clear glaze ice that can attain spectacular formations. For temperatures well below freezing the drops freeze instantaneously forming a rime ice which is not quite as aerodynamically troublesome as the glaze ice. Additionally, for colder temperatures the available LWC is normally less than for near freezing temperatures.

Of the three parameters, DS presents the greatest difficulty in both measurement and calculation. Drop size distributions are

sensitive to the cloud condensation nuclei, strength of vertical motion, mixing of clouds and cloud free air, and cloud lifetime. These factors have defied the concerted attention of a number of investigators so that there is no general method for their accounting. In addition, it is currently difficult or impossible to specify vertical motion, cloud mixing, or cloud lifetime.

Fortunately there may be a way out of this dilemma. Newton (1978) presented results that support the substitution of a median volume drop (MVD) in place of a drop spectrum. Theoretical and experimental studies can determine the reasonableness of such an approximation. With an assumed drop size it is still necessary to measure or infer the temperature and the cloud phase. LWC is critically important as it is directly related to the degree of ice accretion, and phase determines whether the cloud particles will adhere to the aircraft.

3.2 MODELING CANDIDATES

3.2.1 Smith-Feddes Model

The Smith-Feddes Model predicts estimates of LWC, cloud phase, and drop size distribution. The output grid is the same as the Air Force Global Weather Central's (AFGWC) 3DNEPH (three-dimensional nephanalysis) with 15 vertical layers whose thickness varies with altitude. The model input consists of the 3DNEPH analysis of cloud type, the AFGWC analysis of grid temperatures interpolated to the 3DNEPH grid, as well as information about precipitation. For a given cloud type and temperature there is a maximum LWC which is tabularly assigned by the model. This maximum LWC is modified by the in cloud location of the grid point and the cloud type.

The portion of cloud water which is unfrozen varies from 100% at 0°C to 0% at -40°C and is based on Russian data. Finally, drop size distributions are assigned according to the cloud type following the distributions presented by Diem (1948).

3.2.2 Updated Smith-Feddes Model

Rogers et al. (1985a) detail the updating of the original Smith-Feddes model discussed above. The updated version accepts input from the improved cloud analysis model (RTNEPH) and considerably differs in microphysical parameterizations from the original model. This updated version is based on the most recent microphysical observations available at the time of the above report. There is no need in this report to detail the conversion from accepting 3DNEPH to accepting RTNEPH input, however, the microphysical changes are briefly described below.

In examining data on the vertical distribution of LWC, the authors above noted that the profiles in some cases were close approximations of the adiabatic LWC profile and if not were some fraction of the adiabatic LWC. In general, they believed that stratus and stratocumulus clouds closely profile the adiabatic profile while cumulus clouds diverted with height from the adiabatic profile. The authors believed that a function of the adiabatic profile with height would account for the diminishment of the ratio of actual LWC to adiabatic LWC.

The implemented adiabatic computation of LWC consists of several steps. From cloud base the moist adiabatic lapse rate is used to calculate the temperature in 100 m increments above cloud base. These temperatures define the satuaration vapor pressures at 100 m increments through the cloud. Finer resolution in the calculation of saturation vapor pressure is possible, but is not significant in affecting the cloud LWC. The difference in saturation vapor pressure over a 100 m interval defines the additional condensed moisture, that is accumulated beginning at cloud base and continuing to the cloud top. Near cloud top, LWC is diminished somewhat to account for enhanced mixing of unsaturated air above the cloud.

Reduction of adiabatic LWC due to entrainment follows Warner (1970). The adjustment consists of:

$$LWC/LWC_a = az + b \qquad (3.1)$$

where

LWC_a = adiabatic LWC,

z = height above cloud base, and

a,b = parameters which are in turn assigned according to z.

This reduction is applied in the event of stratocumulus, altocumulus, cumulus, and cumulonimbus clouds. No reduction for entrainment was originally applied for stratus or altostratus.

In the Smith-Feddes model the drop size distribution is computed from a parameterized equation so that the number of drops in a given drop diameter interval is the fraction of total LWC in that drop size interval divided by the mass of a single droplet of that size. The fractional LWC follows the Diem distribution curves and is based on cloud type. The parametric equation is designed primarily to give the correct mode of the drop size distribution as well as the percent of LWC at the mode as a function of cloud type. Unfortunately, as shown later, it appears that this approach is overspecified and as a result, the method greatly overestimates the number of larger drops.

3.2.3 Adiabatic LWC

Adiabatic LWC can be calculated from rawinsonde, satellite, or profiler soundings of temperature and humidity. The method involves calculating the cloud base temperature and pressure. With temperature and pressure known at this level, it is possible to infer LWC for higher heights based on adiabatic parcel ascent from this level. This method does not address entrainment of dryer environmental air nor does it allow for precipitation. Observations of cloud LWC values typically are less than adiabatic and the ratio of actual LWC to adiabatic LWC decreases from cloud base to cloud top. The validity of this method is also limited to convective clouds.

An extension of this method has been developed by the Air Weather Service (1969). The AWS method involves using a cloud model with a fixed rate of entrainment to calculate the LWC by height. The method pertains to stratiform and convective clouds depending upon the convective stability. For stratiform cloud which must be inferred from temperature and dew-point spread, the calculated LWC is halved. Finally a median volume drop diameter (MVD) size of 14 μm for stratiform clouds and 17 μm for convective clouds is specified. These values are closely consistent with those reported by Jeck (1983) who summarized the available continental United States observations of temperature, LWC, and DS. Jeck shows that MVD values vary from about 5 μm to about 30 μm for convective clouds. A desirable improvement to this method would be to specify the MVD size according to environmental conditions. Newton (1978) reported good comparison between estimated LWC and ice accretion using this method and that actually measured.

3.2.4 AFCRL First Generation Model (AFCRL-I)

Cunningham and Pierce (1974) employs a decision tree approach in calculating LWC and precipitation phase. Temperatures of -10°C, -15°C, and 0°C designate respectively transitions between ice crystals, small snow, large snow, and rain. The LWC values are typical values.

The model input includes a sounding in addition to the current weather and intensity of precipitation; the type of low cloud gives an indication of presence or absence of convective activity.

3.2.5 AFCRL Second Generation Model (AFCRL-II)

The second generation model depends on preparation of vertical time height across sections to which LWC values are added (Cunningham and Pierce 1974). The cross sections include:

(1) Surface observation of weather, precipitation type and amount, sky cover, cloud type and amount, cloud base heights, winds, temperatures, dew-point, and pressure.

(2) Temperature, dew-point temperature depression, and winds for significant and special levels in the vertical. Satellite visual and infrared photographs, surface synoptic maps, and 3DNEPH analyses are also used. The cross sections are analyzed for stable and conditionally unstable layers to which cloud patterns are added. Values of LWC and hydrometeor concentrations are assigned according to published values in the literature. In this form the model is unsuitable for computer programming.

3.2.6 Meteorology Research Inc. Models (MRI)

The MRI models MRI-RH and MRI-VV are respectively for relative humidity and vertical velocity (Heymsfield and Howard 1975). These models represent an attempt to develop nomograms for assigning LWC by cloud and weather type. The nomograms are formulated on the basis of vertical moisture flux between atmospheric levels. For the vertical velocity nomogram it is necessary to calculate a profile of vertical velocioty.

Pierce et al. (1975) compared the performance of several of the above model (not including the updated Smith-Feddes model) that prescribe LWC with a limited number of observations. These are shown in Figures 3.1a and 3.1b. The comparisons are not terribly encouraging, however, as shown later the updated Smith-Feddes model shows skill in predicting LWC.

3.2.7 Matveev

Matveev (1984) presented a discussion on the calculation of

$$Q_\delta = \int_{Z_L}^{Z_U} \rho\delta dz \qquad (3.2)$$

where Q_δ is the integrated cloud water content and Z_L and Z_U are the cloud base and cloud top heights, respectively. The method involves using a simplified version of the equation for conservation of moisture to which equations for heat content, vertical

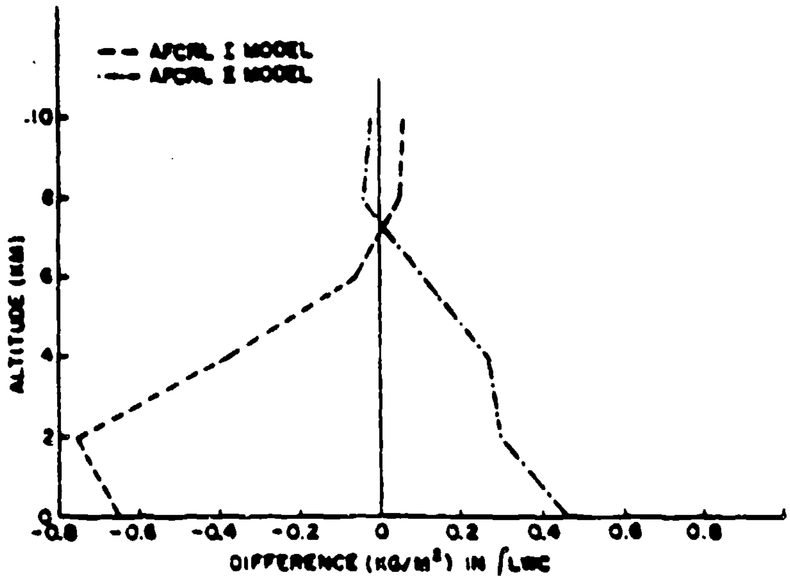

Figure 3.1a. Mean Difference in Integrated Liquid Water Content Between Observed and Deduced Values for AFCRL I and AFCRL II.

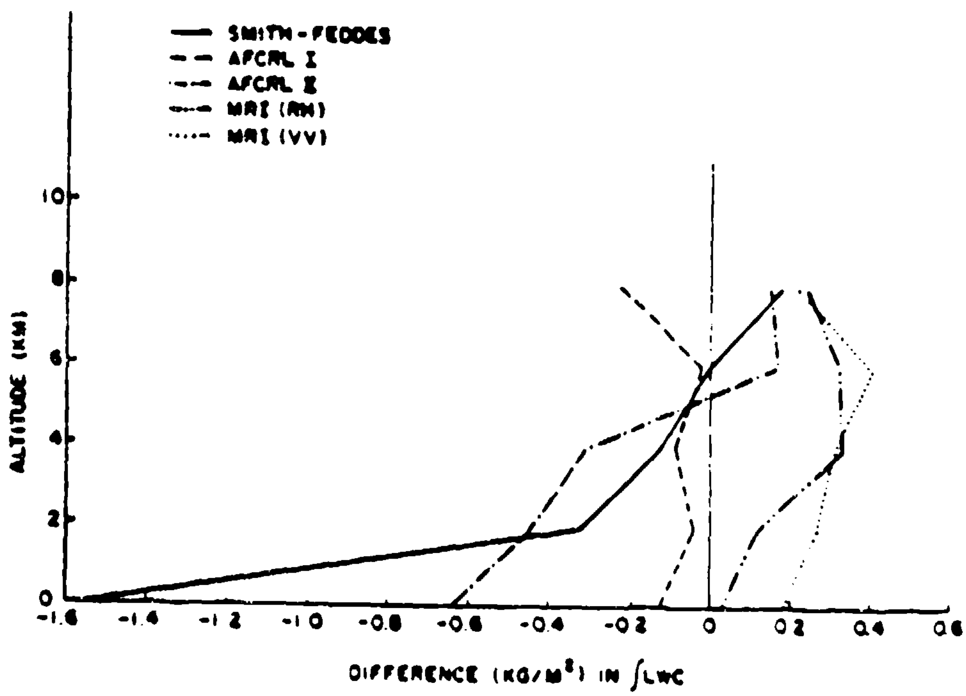

Figure 3.1b. Mean Difference in Integrated Liquid Water Content Between Observed and Deduced Values for All Models; Twelve Cases Only.

velocity, and the turbulence coefficient are added. For this method the fall velocity of cloud elements was assumed independent of height. The resulting equation set was solved numerically by the Runge-Kutta method. A temperature profile from a radiosonde or the like may be used in place of the heat content equation. Matveev claims good comparison of Q_{δ} calculated by this method to values measured by aircraft. Q_{δ} has a strong dependence on ground level temperature which has been verified. However, other theoretical relationships with the vertical velocity, turbulent mixing, and drop fall velocities and turbulence coefficients which require diagnosis or calculation by other sophisticated models such as those discussed next. Finally, Q_{δ} is an integrated rather than a point value.

3.2.8 Other Models

Recent developments in cloud and mesoscale modeling (Klemp and Wilhelmson 1978, Jun and Hsu 1984) enable grid point calculation of LWC. The calculations range from microphysical parameterizations such as Kessler (1969) or Sundqvist (1981) to detailed microphysical calculations (Silverman and Glass 1985). In the latter case the resulting drop spectrum as well as LWC is calculated. For convective clouds the model present a feasible means for alternate data development, however, their computational and input data requirements are quite stringent. In this sense, the Silverman and Glass 1-dimensional model is attractive as it only requires a single input sounding; on the other hand, most 1-dimensional models overpredict LWC for cases of environmental wind shear (Cotton and Tripoli 1978) so such a model has limited validity. For stratiform clouds it is necessary to have detailed 3-dimensional calculation so that vertical motions can be faithfully portrayed.

3.3 REMOTE SENSING

Passive and active microwave sensors are promising means for obtaining LWC in clouds (Devault and Katsaros 1983, Rauber et al. 1982), however, they are currently restricted to integrated values

(Shepard 1985). Current satellite instruments are limited in the number of available microwave channels and this is likely to remain the case into the next decade. Thereafter, with more channels available it may be possible by inversion techniques to derive a vertical profile of LWC.

Ground based methods for calculating LWC seem to be further along in development. Rauber et al. (1982) report on favorable comparisons between radiometer measured values of LWC to those measured by a research aircraft. One goal of a field study recently completed in Louisiana was to test a tomographic technique which can yield a profile of LWC (Knight 1985). It will be some time before the data from this study can be fully evaluated.

Although remote sensing methods seem to offer good future prospects for regular observation of LWC, it is currently possible to only calculate the vertically integrated amount. This amount can serve to calibrate a method such as the updated Smith-Feddes which provides vertical detail of the LWC distribution. In addition for ground based systems there is the problem of deployment especially over oceanic and mountainous regions which unfortunately seem to be prime locations for aircraft icing occurrence.

3.4 VALIDATION OF THE UPDATED SMITH-FEDDES MODEL

Based on the review of modeling candidates in Section 3.2 and of remote sensing techniques in Section 3.3, it became apparent that the updated Smith-Feddes model offered the best promise as an alternate data development scheme. The model was untested, however, so a thorough validation was in order before an unfettered recommendation could be made. The FAA/NRL icing data base was an obvious means for the validation provided that input data was available to satisfy the Smith-Feddes requirements. For a number of data base measurements, supplementary data from the measuring aircraft or a conjunctive rawinsonde sounding was available. After some manipulation it was possible to calculate temperature, LWC, and drop size distribution with the Smith-Feddes

model and then compare the predicted value to the measured value in the data base.

3.4.1 Preparation of Smith-Feddes Input Data

One of the options for running the updated Smith-Feddes model is via a card image file (Rogers 1985b). The required file consists of the following: latitude and longitude for the calculation position; present weather, visibility and time for the calculation point; total percent cloud cover and partial percent cloud cover for each cloud deck (up to 4 decks); coded input for the type of cloud; cloud base and cloud top heights for each cloud deck; surface elevation for the calculation position; heights in meters of the standard pressure levels of 1000, 850, 700, 500, 400, 300, 200, 150, and 100 mb; and temperatures in degrees Kelvin at the standard pressure levels and at the surface.

In many of the data base entries only the measured or estimated cloud base heights, type of precipitation if any, surface elevation, and cloud type were available. Thus, supplementary sources were necessary to obtain standard and special pressure level temperatures and heights. In some cases, the aircraft measured temperature, pressure, and altitude in conjunction with daily weather map surface and 500 mb analyses were sufficient. In the case of the Spanish PEP data it was necessary to obtain the standard and special pressure level heights by hydrostatically integrating the available temperature and pressure soundings. Regardless of these difficulties a total of about 100 comparisons were made. This represents about 50% of the total measurements included in the data base. It was not possible to use any NACA measurements since supplementary data for standard level heights and temperatures was unavailable.

3.4.2 Philosophy for Comparison of Smith-Feddes Calculated LWC, T, and DS to FAA/NRL Observations

The FAA/NRL data base of supercooled LWC measurements is organized according to the collecting agency, time, cloud, and event. A given "cloud" corresponds to one cloud base

height and environmental sounding and might include several "events". (See Jeck 1983 for details of cloud and event definition.) Since the Smith-Feddes model was originally designed for data with 25 nautical mile horizontal resolution, we decided to compare average FAA/NRL "cloud" values of LWC, T, and DS to the Smith-Feddes calculations. For a cloud, there may be several events which are representative of a finer scale than is appropriate to the Smith-Feddes calculations. In addition, this larger scale is more relevant to aircraft icing since an aircraft is not immediately disabled by penetrating small regions of high LWC content nor is it immediately unburdened of ice when transiting small scale unsaturated regions. The general trend of ice accretion over a 10 mile or larger distance should then correlate reasonably well with average cloud values as described above.

3.4.3 Changes to Updated Smith-Feddes Model

During an initial validation, several deficiencies of the updated Smith-Feddes were noted. The model appeared to calculate slightly too much LWC for stratus clouds and too little LWC for stratocumulus and cumulus clouds. In addition, considerable scatter between calculated and observed LWC values was noted for all clouds. Smith-Feddes calculated MVD values were in significant disagreement with those observed and the Smith-Feddes drop size calculation procedure was identified as unlikely to produce realistic MVD values.

The LWC discrepancies were attributed to two sources: incorrect cloud base temperature or improper accounting for the mixing of cloudy and unsaturated air. The first source was ameliorated by allowing the model greater vertical resolution of input temperature and heights versus pressure. This allowed a properly identified cloud base temperatures which are associated with frontal inversions or the like which are poorly resolved by standard pressure level data alone.

The second source was not as easily handled. In general, sub-adiabatic LWC values exist in the bulk of convective clouds and also apparently for many layer clouds. Precipitation

and entrainment of dryer external air contributes to the diminishment of LWC values. Entrainment may take the form of organized inflow of external air similar to that observed for laboratory plumes, via turbulent mixing driven by shear and buoyant energy production, or via internal penetrative plumes which arise from mixing near the cloud top of cloudy and cloud free air. Precise modeling of all these processes is currently impossible even in the very sophisticated three-dimensional models of deep convection (see Section 3.2.8). Crude but reasonable parameterization of cloud microphysics and turbulence is necessary. Favorable comparisons between observed and calculated LWC values for layer clouds were obtained for the Smith Feddes model when the Warner reduction curve was used for stratus clouds and the Skatskii reduction curve for stratocumulus clouds (Figure 3.2). For convective clouds the Skatskii (1965) reduction curve gives superior results to the Warner curve. Despite the reasonable LWC values, the calculated drop size distributions remain uniformly unrealistic.

We have not currently rectified the drop distribution problem, however, we can suggest a procedure that is expected to greatly improve DS calculation. Following Johnson (1986) and Berry and Reinhart (1974) the cloud droplet distribution in many cases can be described by a gamma distribution as

$$f\langle x\rangle = \frac{N^2}{LWC} \; G(\gamma) \; S^{\gamma} \; e^{-(1+\gamma)S} \tag{3.3}$$

where

$$S = \frac{Nx}{LWC} \tag{3.4}$$

$$G(\gamma) = \frac{(1+\gamma)^{1+\gamma}}{\Gamma(1+\gamma)} \tag{3.5}$$

and where $f\langle x\rangle$ is the number density of drops of mass x, N is the total number of cloud droplets per unit volume and γ is the shape parameter which specifies the distribution breadth. Although $\gamma = 2$

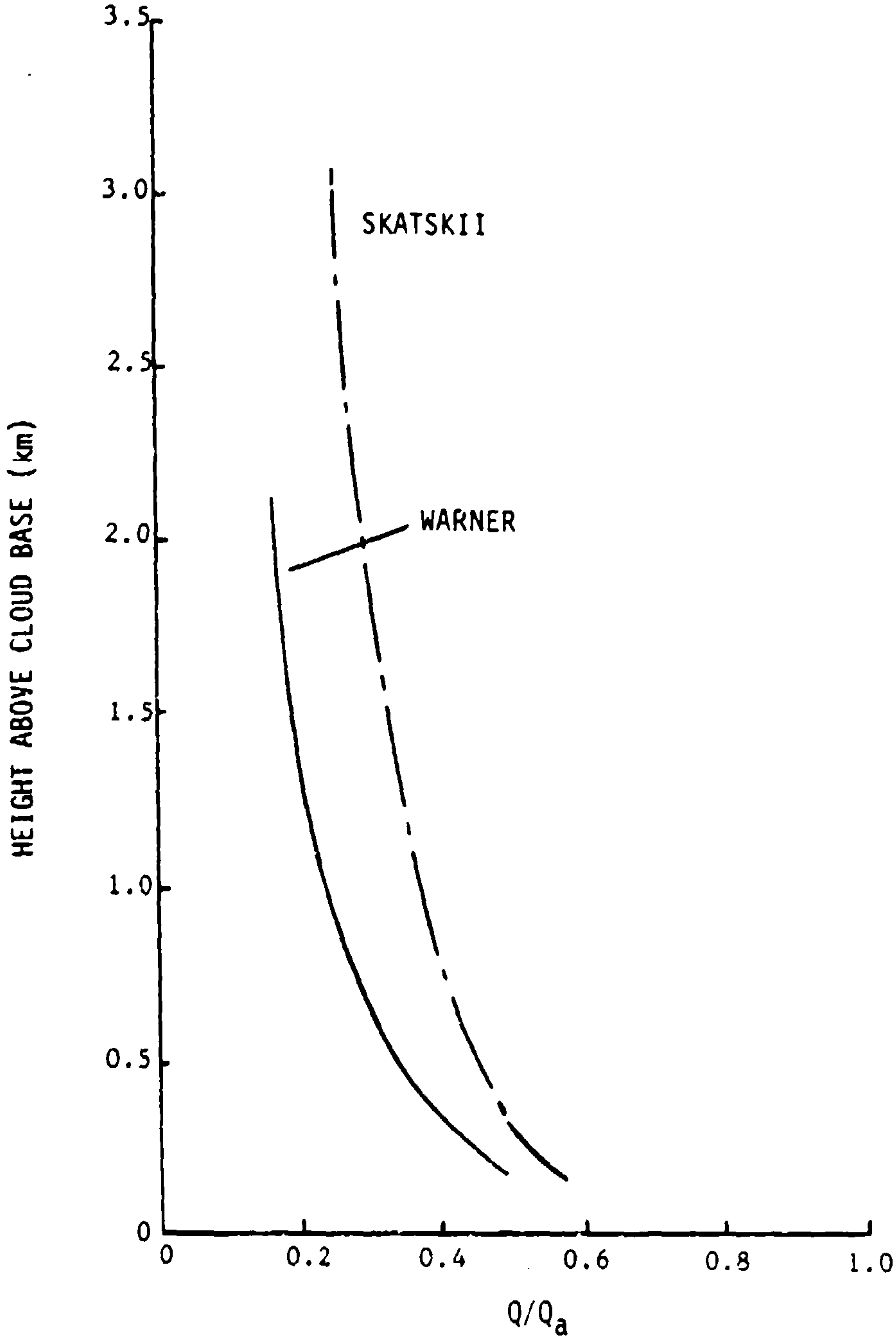

Figure 3.2 Ratio of Observed Liquid Water Content (A) to Adiabatic Liquid Water Content (Q_a) as A Function of Height Above Cloud Base from Warren (1970).

seems appropriate for many observed distributions, it might be necessary to reduce γ with height down to as low as 0 to account for the behavior of some observed distributions with height. It may be possible to relate γ to environmental parameters such as cloud location, height of cloud base, season, wind shear, CCN, etc.

At any rate, integrating equation (3.3) over x can yield the total cloud droplet number per unit volume

$$N = \int f\langle x\rangle \, dx \tag{3.6}$$

and the liquid water content

$$LWC = \int x \, f\langle x\rangle \, dx. \tag{3.7}$$

With LWC already known from the Smith-Feddes calculations it is possible to infer N and hence the drop size MVD. The key issue is proper selection of γ in terms of environmental parameters, however, even a default calculation in which γ is specified as 2 would yield useful results.

3.4.4 Comparison of Smith-Feddes Calculated LWC, T, and DS Values to FAA/NRL Observations

Table 3.1 lists the calculated and observed temperatures, MVD and LWC values for all validation cases. The Table 3.1 arrangement corresponds to the order in the FAA/NRL data base for ease in cross referencing. Each entry in Table 3.1 lists the location and collecting agency of the observation, the cloud number which corresponds to the FAA/NRL data base entry, the date, cloud type, average LWC measured respectively by the Johnson-Williams and FSSP devices, the LWC calculated by the model, the mean altitude of the observation, and the calculated and observed cloud base temperature. In general, these latter two numbers agree closely, however, in a few instances it was difficult for the model to properly resolve strong inversions. Cloud base temperature difference, however, is not the main contributor to differences in observed and calculated LWC values. As mentioned

TABLE 3.1

COMPARISON OF CALCULATED AND OBSERVED TEMPERATURE, MVD, AND LWC

LOCATION, AGENCY, & FLIGHT	CLOUD NO.	DATE	CLOUD TYPE	LIQUID WATER CONTENT: JOHNSON/WILLIAMS	LIQUID WATER CONTENT: PARTICLE SPECTROMETER	LIQUID WATER CONTENT: SMITH-FEDDES	MEAN ALTITUDE (meters)		CLOUD BASE TEMPERATURE (°C)
Central Lake Michigan (UWY)	1	12/3/80	Sc	0.12	0.13	0.23	865	OBS CALC	-7.3 -4.7
Central Lake Michigan (UWY)	1	12/10/80	Sc	0.32	0.25	0.22	1475	OBS CALC	-8.0 -8.7
Central Lake Michigan (UWY)	2	12/10/80	Sc	0.14	0.12	0.17	987	OBS CALC	-8.9 -8.7
Muskegon, Lake Michigan (UWY)	1	12/13/80	Sc	0.18	0.17	0.10	1532	OBS CALC	-15.4 -14.7
Muskegon, Lake Michigan (UWY)	3	12/13/80	Sc	0.11	0.10	0.10	1410	OBS CALC	-14.5 -13.7
Central Lake Michigan (UWY)	2	12/13/80	Sc	0.11	0.11	0.08	1130	OBS CALC	unknown
Central Lake Michigan (UWY)	1	12/16/80	St	0.04	0.02	0.08	3814	OBS CALC	-19.0 -18.7
Central Lake Michigan (UWY)	2	12/16/80	St	0.20	0.17	0.12	1463	OBS CALC	-10.7 -11.2
Central Lake Michigan (UWY)	3	12/16/80	St	0.04	0.05	0.08	2543	OBS CALC	-14.7 -15.4

TABLE 3.1 (continued)

LOCATION, AGENCY, & FLIGHT	CLOUD NO.	DATE	CLOUD TYPE	LIQUID WATER CONTENT JOHNSON/WILLIAMS	LIQUID WATER CONTENT PARTICLE SPECTROMETER	LIQUID WATER CONTENT SMITH-FEDDES	MEAN ALTITUDE (meters)		CLOUD BASE TEMPERATURE (°C)
La Junta, Colorado (UWY)	2	12/19/80	St	0.03	0.07	0.07	2352	OBS CALC	-10.0 -8.5
Dalhart, Texas (UWY)	4a	12/19/80	St	0.06	0.07	0.06	2667	OBS CALC	-11.2 -10.7
Akron, CO (UWY)	6	12/19/80	St	0.10	0.16	0.19	2380	OBS CALC	-13.3 -10.2
Lake Michigan #3 (UWY)	1	1/7/81	St	0.13	0.13	0.13	1465	OBS CALC	-18.5 -16.7
Lake Michigan #4 (UWY)	A	1/8/81	Sc	0.17	0.16	0.13	1678	OBS CALC	-17.0 -16.9
Lake Michigan #4 (UWY)	B	1/8/81	Sc	0.22	0.14	0.12	1071	OBS CALC	-16.6 -15.8
Lake Michigan #4 (UWY)	C	1/8/81	Sc	0.20	0.18	0.10	1669	OBS CALC	-16.6 -17.8
Lake Michigan #5 (UWY)	1	1/11/81	St	0.07	0.06	0.07	950	OBS CALC	-18.1 -18.0
Lake Michigan #5 (UWY)	2	1/11/81	St	0.09	0.08	0.08	1088	OBS CALC	-18.0 -18.5

TABLE 3.1 (continued)

LOCATION, AGENCY, & FLIGHT	CLOUD NO.	DATE	CLOUD TYPE	LIQUID WATER CONTENT: JOHNSON/WILLIAMS	LIQUID WATER CONTENT: PARTICLE SPECTROMETER	LIQUID WATER CONTENT: SMITH-FEDDES	M[illegible] ALTITUDE (meters)		CLOUD BASE TEMPERATURE (°C)
Lake Michigan #5 (UWY)	3	1/11/81	St	0.13	0.12	0.05	1354	OBS CALC	-19.3 -20.2
Lake Michigan #6 (UWY)	1	1/12/81	St	0.20	0.17	0.16	830	OBS CALC	-8.8 -12.2
Lake Michigan #6 (UWY)	1a	1/12/81	Sc	0.12	0.09	0.13	824	OBS CALC	-8.8 -12.2
Lake Michigan #6 (UWY)	1b	1/12/81	St	0.16	0.13	0.14	646	OBS CALC	-7.5 -12.2
Lake Michigan #6 (UWY)	2b	1/12/81	St	0.13	0.14	0.14	1169	OBS CALC	-12.9 -12.2
Lake Michigan #6 (UWY)	1c	1/12/81	Sc	0.24	0.18	0.17	1009	OBS CALC	-7.7 -12.2
Lake Michigan #6 (UWY)	2a	1/12/81	St	0.07	0.08	0.06	1202	OBS CALC	-10.4 -12.2
Lake Michigan #7 (UWY)	1	1/14/81	Sc	0.11	0.11	0.13	1706	OBS CALC	-10.4 -10.0
Lake Michigan #7 (UWY)	2	1/14/81	St	0.17	0.14	0.19	1653	OBS CALC	-8.6 -9.0

TABLE 3.1 (continued)

LOCATION, AGENCY, & FLIGHT	CLOUD NO.	DATE	CLOUD TYPE	LIQUID WATER CONTENT JOHNSON/ WILLIAMS	PARTICLE SPECTROMETER	SMITH-FEDDES	MEAN ALTITUDE (meters)		CLOUD BASE TEMPERATURE (°C)
Lake Michigan #7 (UWY)	3	1/14/81	St	0.03	0.07	0.07	1806	OBS CALC	-10.8 -10.4
Goodland, Kansas (GLD)	1	1/30/81	Sc	0.18	0.19	0.16	1508	OBS CALC	-8.9 -9.5
Garden City, Kansas (GCK)	2	1/30/81	Sc	0.15	0.20	0.17	1194	OBS CALC	-6.5 -8.3
Dodge City, Kansas (DDC)	3	1/30/81	Sc	0.18	0.21	0.19	1131	OBS CALC	-5.6 -8.2
Western Kansas (WKS)	4	1/30/81	Sc	0.18	0.13	0.19	1418	OBS CALC	-5.7 -8.3
McCook, Nebraska (UWY)	5	1/30/81	St	0.11	0.09	0.14	1227	OBS CALC	-8.7 -8.6
North Platte, Nebraska (LBF)	1	1/31/81	Sc	0.10	0.10	0.15	1734	OBS CALC	-8.3 -8.4
North Platte, Nebraska (UWY)	2	1/31/81	St	0.03	0.04	0.06	2520	OBS CALC	-11.0 -11.8
North Platte, Nebraska (LBF)	3	1/31/81	St	0.08	0.09	0.06	3665	OBS CALC	-9.7 -11.2

TABLE 3.1 (continued)

LOCATION, AGENCY, & FLIGHT	CLOUD NO.	DATE	CLOUD TYPE	LIQUID WATER CONTENT JOHNSON/WILLIAMS	LIQUID WATER CONTENT PARTICLE SPECTROMETER	SMITH-FEDDES	MEAN ALTITUDE (meters)		CLOUD BASE TEMPERATURE (°C)
North Platte, Nebraska (UWY)	4	1/31/81	St	0.01	0.01	0.03	4474	OBS CALC	-16.7 -18.2
Mc Clellan AFB California (UWY) Sierra Co-Op	STS A	2/14/79	Cu	0.32	0.48	0.59	2156	OBS CALC	0.0 0.1
Mc Clellan AFB California (UWY) Sierra Co-Op	STS A	2/14/79	Cu	0.44	0.50	0.53	1969	OBS CALC	0.0 0.1
Mc Clellan AFB California (UWY) Sierra Co-Op	STS A	2/14/79	Cu	0.59	0.74	0.65	2419	OBS CALC	0.0 0.1
Mc Clellan AFB California (UWY) Sierra Co-Op	STS A	2/14/79	Cu	0.46	0.44	0.60	2195	OBS CALC	0.0 0.1
Mc Clellan AFB California (UWY) Sierra Co-Op	STS A	2/14/79	Cu	0.63	0.68	0.66	2438	OBS CALC	0.0 0.1
Mc Clellan AFB California (UWY) Sierra Co-Op	STS A	2/14/79	Cu	0.55	0.59	0.65	2425	OBS CALC	0.0 0.1
Mc Clellan AFB California (UWY) Sierra Co-Op	STS A	2/14/79	Cu	0.29	0.33	0.66	2438	OBS CALC	0.0 0.1
Mc Clellan AFB California (UWY) Sierra Co-Op	STS A	2/14/79	Cu	0.51	0.44	0.66	2438	OBS CALC	0.0 0.1

TABLE 3.1 (continued)

LOCATION, AGENCY, & FLIGHT	CLOUD NO.	DATE	CLOUD TYPE	LIQUID WATER CONTENT: JOHNSON/ WILLIAMS	LIQUID WATER CONTENT: PARTICLE SPECTROMETER	LIQUID WATER CONTENT: SMITH-FEDDES	MEAN ALTITUDE (meters)		CLOUD BASE TEMPERATURE (°C)
Mc Clellan AFB California (UWY) Sierra Co-Op	SYS A	2/14/79	Cu	0.57	0.51	0.68	2598	OBS CALC	0.0 0.1
Mc Clellan AFB California (UWY) Sierra Co-Op	SYS A	2/14/79	Cu	0.30	0.44	0.70	2736	OBS CALC	0.0 0.1
Mc Clellan AFB California (UWY) Sierra Co-Op	SYS A	3/18/79	Cu	0.43	0.69	0.67	2872	OBS CALC	0.1 0.5
Mc Clellan AFB California (UWY) Sierra Co-Op	SYS A	3/18/79	Cu	*	1.02	0.72	3085	OBS CALC	0.1 0.5
Blue Canyon California (UWY) Sierra Co-Op	SYS A	3/18/79	Cu	0.28	0.48	0.68	2888	OBS CALC	0.1 0.5
Blue Canyon California (UWY) Sierra Co-Op	SYS A	3/18/79	Cu	*	0.31	0.70	2974	OBS CALC	0.1 0.5
Blue Canyon California (UWY) Sierra Co-Op	SYS A	3/18/79	Cu	0.23	0.28	0.61	2621	OBS CALC	0.1 0.5
Blue Canyon California (UWY) Sierra Co-Op	SYS A	3/18/79	Cu	0.58	0.31	0.59	2448	OBS CALC	0.1 0.5
Blue Canyon California (UWY) Sierra Co-Op	SYS A	3/18/79	Cu	0.23	0.26	0.59	2408	OBS CALC	0.1 0.5

TABLE 3.1 (continued)

LOCATION, AGENCY, & FLIGHT	CLOUD NO.	DATE	CLOUD TYPE	LIQUID WATER CONTENT JOHNSON/WILLIAMS	PARTICLE SPECTROMETER	SMITH-FEDDES	MEAN ALTITUDE (meters)		CLOUD BASE TEMPERATURE (°C)
Olympia, Washington (UWSH) F857CL	A	2/14/80	Ac	0.07	0.12	0.07	3950	OBS CALC	-17.8 -19.1
Hoquiam Washington (UWSH) F857CL	B	2/14/80	Sc	0.04	0.15	0.26	1373	OBS CALC	-4.1 -1.9
Hoquiam, Washington (UWSH) F857CL	C	2/14/80	Sc	0.07	0.12	0.13	1235	OBS CALC	-2.6 -2.4
Hoquiam, Washington (UWSH) F857CL	D	2/14/80	St	0.07	0.17	0.16	1081	OBS CALC	-3.4 -3.9
Hoquiam, Washington (UWSH) F857CL	G	2/14/80	Sc	0.08	0.21	0.17	1637	OBS CALC	-4.0 -3.9
Hoquiam, Washington (UWSH) F857CL	H	2/14/80	Sc	0.05	0.1[illegible]	0.13	1117	OBS CALC	-2.9 -1.9
Hoquiam, Washington (UWSH) F857CL	I	2/14/80	Sc	0.06	0.10	0.10	1518	OBS CALC	-3.8 -3.9
Olympia, Washington (UWSH) F881CL	A	4/9/80	Cu	*	0.97	0.58	1868	OBS CALC	-0.4 -1.2
Hoquiam, Washington (UWSH) F881CL	B	4/9/80	Cu	*	0.66	0.32	1417	OBS CALC	1.0 1.2

TABLE 3.1 (continued)

LOCATION, AGENCY, & FLIGHT	CLOUD NO.	DATE	CLOUD TYPE	LIQUID WATER CONTENT JOHNSON/ WILLIAMS	PARTICLE SPECTROMETER	SMITH-FEDDES	MEAN ALTITUDE (meters)		CLOUD BASE TEMPERATURE (°C)
Valladolid, Spain (LAMP) F3	SYS A	3/27/79	Sc	0.31	0.41	0.32	1922	OBS CALC	1.0 3.8
Valladolid, Spain (LAMP) F3	B	3/27/79	As	0.26	0.28	0.31	3270	OBS CALC	-9.0 -5.4
Santiago, Spain (LAMP) F3	C	3/27/79	Cu	0.70	0.49	0.70	1786	OBS CALC	6.0 7.9
Santiago, Spain (LAMP) F4	A	3/27/79	Sc	0.54	0.81	0.91	2[illegible]59	OBS CALC	7.0 8.9
Valladolid, Spain (LAMP) F4	B	3/27/79	As	0.18	0.15	0.13	2509	OBS CALC	-3.0 -4.7
Valladolid, Spain (LAMP) F4	C	3/27/79	Sc	0.25	0.23	0.38	2095	OBS CALC	3.0 3.8
Valladolid, Spain (LAMP) F5	A	3/28/79	Sc	0.59	0.50	0.60	2741	OBS CALC	-4.0 -2.4
Valladolid, Spain (LAMP) F6	B	3/28/79	Cu	0.59	0.50	0.50	3272	OBS CALC	-1.0 -6.4
Valladolid, Spain (LAMP) F7	A	3/29/79	Sc	0.47	0.59	0.41	3034	OBS CALC	-3.0 -6.5

TABLE 3.1 (continued)

LOCATION, AGENCY, & FLIGHT	CLOUD NO.	DATE	CLOUD TYPE	LIQUID WATER CONTENT JOHNSON/ WILLIAMS	PARTICLE SPECTROMETER	SMITH-FEDDES	MEAN ALTITUDE (meters)		CLOUD BASE TEMPERATURE (°C)
Valladolid, Spain (LAMP) F7	B	3/29/79	Sc	0.36	0.35	0.39	3500	OBS CALC	-8.0 -8.3
Valladolid, Spain (LAMP) F7	C	3/29/79	Sc	0.32	0.25	0.36	2843	OBS CALC	-3.0 -6.5
Valladolid, Spain (LAMP) F7	D	3/29/79	Sc	0.43	0.38	0.43	3894	OBS CALC	-8.0 -8.3
Santiago, Spain (LAMP) F8	B	3/30/79	Sc	0.53	0.29	0.31	1951	OBS CALC	-1.0 -3.8
Valladolid, Spain (LAMP) F9	SYS B	3/30/79	Cu	0.88	0.63	0.70	3415	OBS CALC	1.0 -1.3
Valladolid, Spain (LAMP) F10	SYS A	3/31/79	Sc	0.49	0.58	0.59	2622	OBS CALC	-1.0 -0.4
Valladolid, Spain (LAMP) F11	SYS A	4/2/79	Sc	0.18	0.24	0.22	2572	OBS CALC	-6.0 -4.2
Valladolid, Spain (LAMP) F03	GRP 1	3/28/81	Cu	0.16	0.15	0.49	2381	OBS CALC	6.0 -1.0
Valladolid, Spain (LAMP) F03	GRP 2	3/28/81	Cu	0.49	0.20	0.86	2619	OBS CALC	6.0 8.9

TABLE 3.1 (continued)

LOCATION, AGENCY, & FLIGHT	CLOUD NO.	DATE	CLOUD TYPE	LIQUID WATER CONTENT JOHNSON/WILLIAMS	LIQUID WATER CONTENT PARTICLE SPECTROMETER	LIQUID WATER CONTENT SMITH-FEDDES	MEAN ALTITUDE (meters)		CLOUD BASE TEMPERATURE (°C)
Valladolid, Spain (LAMP) F06		4/6/81	Cu	0.62	0.70	0.36	2934	OBS CALC	0.0 0.0
Valladolid, Spain (LAMP) F10		4/10/81	Cu	0.73	0.59	0.44	2684	OBS CALC	3.0 3.0
Valladolid, Spain (LAMP) F11		4/13/81	Cu	0.84	0.73	0.45	2776	OBS CALC	2.0 1.4
Valladolid, Spain (LAMP) F12	GRP 1	4/14/81	Cu	0.61	0.51	0.55	2578	OBS CALC	1.0 1.0
Valladolid, Spain (LAMP) F12	GRP 3	4/14/81	Cu	0.53	0.43	0.51	2583	OBS CALC	1.0 3.2
Valladolid, Spain (LAMP) F17		4/25/81	Cu	0.39	0.44	0.51	2399	OBS CALC	0.0 3.7
Valladolid, Spain (LAMP) F18		4/27/81	Cu	0.35	0.44	0.31	2571	OBS CALC	-6.0 -6.3
Valladolid, Spain (LAMP) F19		5/4/81	Ac	0.16	0.09	0.28	2375	OBS CALC	-3.0 0.5
Valladolid, Spain (LAMP) F23		5/9/81	Cu	0.41	0.29	0.48	2249	OBS CALC	2.0 1.2

TABLE 3.1 (concluded)

LOCATION, AGENCY, & FLIGHT	CLOUD NO.	DATE	CLOUD TYPE	LIQUID WATER CONTENT: JOHNSON/WILLIAMS	LIQUID WATER CONTENT: PARTICLE SPECTROMETER	LIQUID WATER CONTENT: SMITH-FEDUCS	MEAN ALTITUDE (meters)		CLOUD BASE TEMPERATURE (°C)
Valladolid, Spain (LAMP) F20		5/7/81	Cu	0.33	0.19	0.30	2741	OBS CALC	-2.0 1.7
Valladolid, Spain (LAMP) F24		5/9/81	Cu	0.45	0.28	0.47	2740	OBS CALC	0.0 -1.4
Valladolid, Spain (LAMP) F26		5/10/81	Cu	0.53	0.39	0.63	3154	OBS CALC	3.0 5.8
Valladolid, Spain (LAMP) F27	CAP 1	5/11/81	Cu	0.43	0.36	0.54	2293	OBS CALC	4.0 5.4
Valladolid, Spain (LAMP) F28		5/13/81	Sc	0.30	0.19	0.33	[illegible]	OBS CALC	1.0 3.4
Valladolid, Spain (LAMP) F29	CAP 1	5/14/81	Sc	0.49	0.41	0.21	[illegible]	OBS CALC	-3.0 -3.5
Valladolid, Spain (LAMP) F29	CAP 2	5/14/81	Cu	[illegible]	[illegible]	0.72	[illegible]	OBS CALC	4.0 5.3

previously, the strength and nature of cloud mixing varies considerably depending on the environment and the Warner and Skatskii reduction curves are only mean summaries of the reduction which has an obvious variance. In addition, there is instrument error which is evident when the two located measuring devices are compared. In general, the LWC comparisons in Table 3.1 for a variety of environments, collecting agencies, and cloud types are quite good.

In our investigation we looked at several methods of evaluating the comparisons of the Smith-Feddes predicted LWC values to those observed by the Johnson-Williams and particle spectrometer measuring devices. We initially performed a least squares fit, on the raw data, to the line of the form

$$Y = m X + b. \tag{3.8}$$

The results from this method gave us an indication of any bias that the model might have. For the cases which compared the Smith-Feddes predicted LWC to the Johnson-Williams and particle spectrometer measured LWC (Figures 3.3 and 3.4, respectively) for all cloud types considered (St, Sc, Ac, and Cu), the linear regressions produced the equations,

$$S\text{-}F = 0.85\ (J\text{-}W) + 0.08 \tag{3.9}$$

and

$$S\text{-}F = 0.81\ (P\text{-}S) + 0.09\ . \tag{3.10}$$

Thus, we see that the bias, if any, in the model is insignificant. For this reason, and the fact that if the measuring devices did not register any LWC at all there would be no clouds and if there are no clouds, then the Smith-Feddes model would also indicate no LWC. Thus, we force our regression line through the origin. The form of the regression line then becomes,

$$Y = m X\ . \tag{3.11}$$

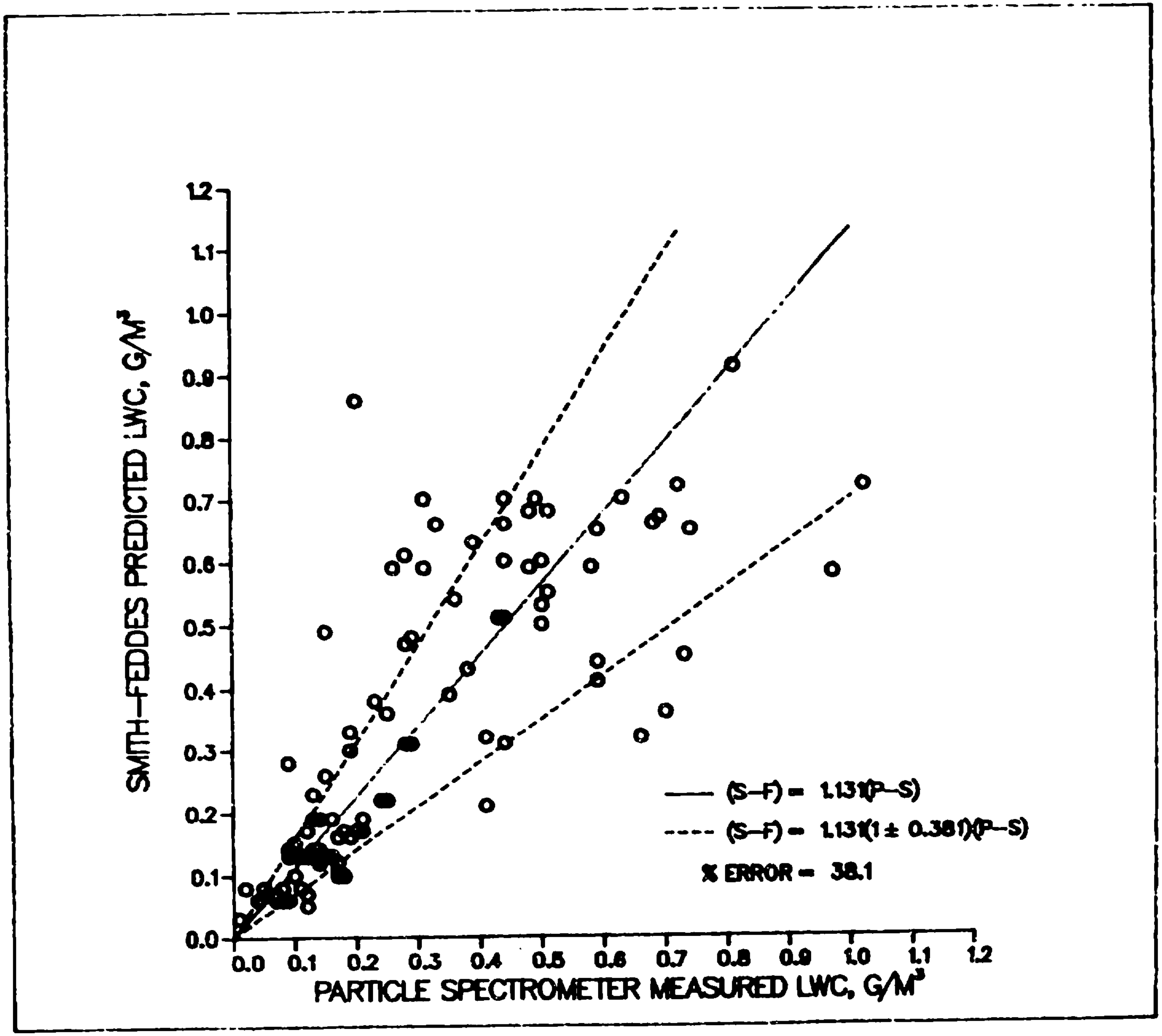

Figure 3.3 P-S Measured LWC vs. S-F Predicted LWC for ST, SC, AC, and CU Cloud Types.

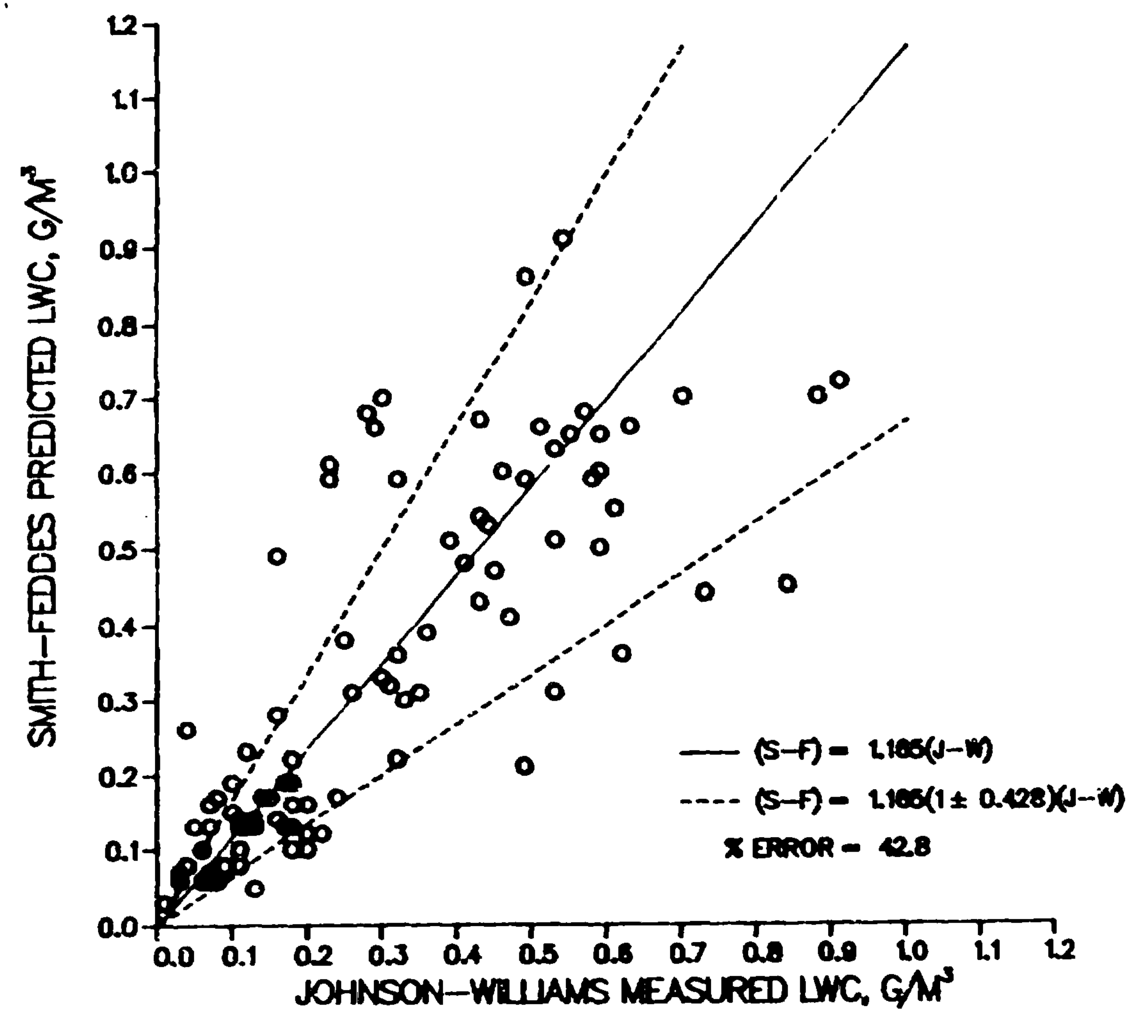

Figure 3.4 J-W Measured LWC vs. S-F Predicted LWC for ST, SC, AC, and CU Cloud Types.

Figures 3.3 and 3.4 show that for larger values of liquid water content, the data points become more spread out. This spreading out, or fanning, of the data indicates that, in this form, the data does not lend itself to a regression analysis, because the more extreme points have a larger influence on the regression line. However, if we go to a logarithmic scale, as in Figure 3.5, we see that the spreading of the data is more uniform, and therefore the influence of the points will be more even.

Thus, the form of the regression line transforms from Eq. (3.11) to

$$\ln Y = \ln X + \ln(m) \; , \tag{3.12}$$

but since m is a constant, $\ln(m)$ is a constant, so let $\ln(m) = b$. Eq. (3.12) can then be rewritten as,

$$\ln(S-F) = \ln(J-W) + b. \tag{3.13}$$

From here we can solve directly for the intercept, b,

$$b = \ln\left(\frac{S-F}{J-W}\right) . \tag{3.14}$$

The linear regression calculation for each of the comparison cases reduces to finding the mean for b, $(\bar{b})$. Thus,

$$\ln(S-F) = \ln(J-W) + \bar{b} \tag{3.15}$$

is the regression line in the $\ln$ vs. $\ln$ space. To return to the unscaled space, all we need to do is perform the inverse logarithm on both sides of Eq. (3.14) to obtain,

$$S-F = e^{\bar{b}} \; J-W \quad \text{or} \quad S-F = m \; J-W \; , \tag{3.16}$$

where

$$m = e^{\bar{b}}. \tag{3.17}$$

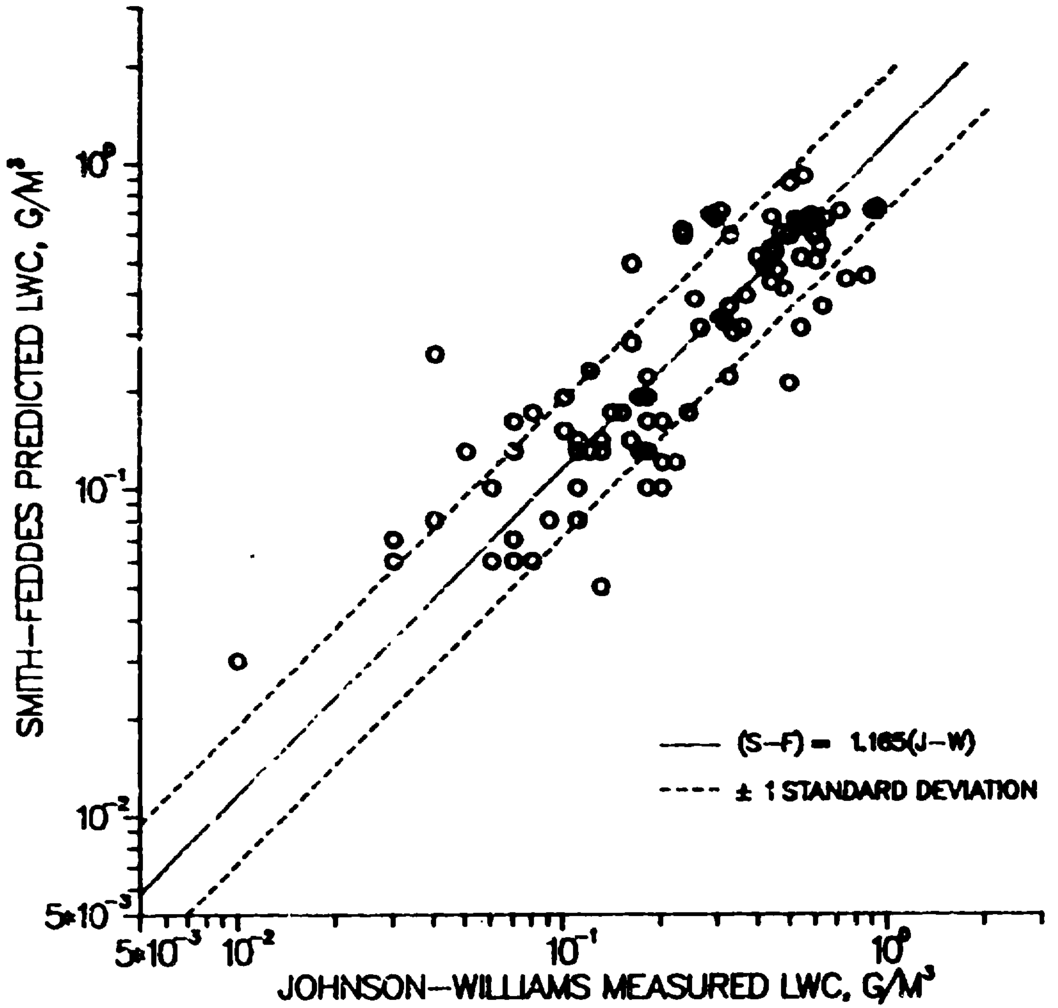

Figure 3.5 J-W Measured LWC vs. S-F Predicted LWC for ST, SC, AC, and CU Cloud Types (log-log scale).

This method was used to calculate the regression lines for each of the comparison cases and the results are displayed in each of their corresponding Figures (. .. - 3.14).

After obtaining the regression lines, the present error in the Smith-Feddes model could be determined for each of the comparison cases. The percent error for each case is the mean of the percent error of each of its individual data points. Thus, if Y is the actual Smith-Feddes value and Y' is its corresponding predicted value (Y' = m X, where X is the corresponding Johnson-Williams or particle spectrometer measured LWC), and n is the number of data points in the comparison case, then the percent error is calculated by,

$$\text{Percent Error} = \frac{100}{n} \sum_{i=1}^{n} \frac{|Y' - Y|}{Y} \quad . \qquad (3.18)$$

The percent error calculations for each of the comparison cases gives an indication of how well the S-F model predicts the LWC.

Figure 3.3 shows the particle spectrometer measured LWC versus the Smith-Feddes calculated LWC for all clouds. Most of the values lie within the dashed line. However, those values that do not, indicate the Smith-Feddes overpredicts LWC. Figure 3.4 shows the same comparison except for the Johnson-Williams device. The results in Figures 3.3 and 3.4 are quite similar with the Smith-Feddes agreeing slightly better with the particle spectrometer (PS) than with the Johnson-Williams (JW). The percent errors between model and observation are nearly the same as for the intercomparison of measuring devices.

Figures 3.6 and 3.7 show the LWC comparisons for respectively the PS and the JW device for stratus clouds. The percent errors are slightly lower than for all the clouds comparison however, the largest stratus LWC is only about 0.2gm/m^3 so that these percent errors translate to fairly low absolute errors. Some measurement errors may be independent of LWC and are relatively large for low LWC values. As is the case for the all cloud

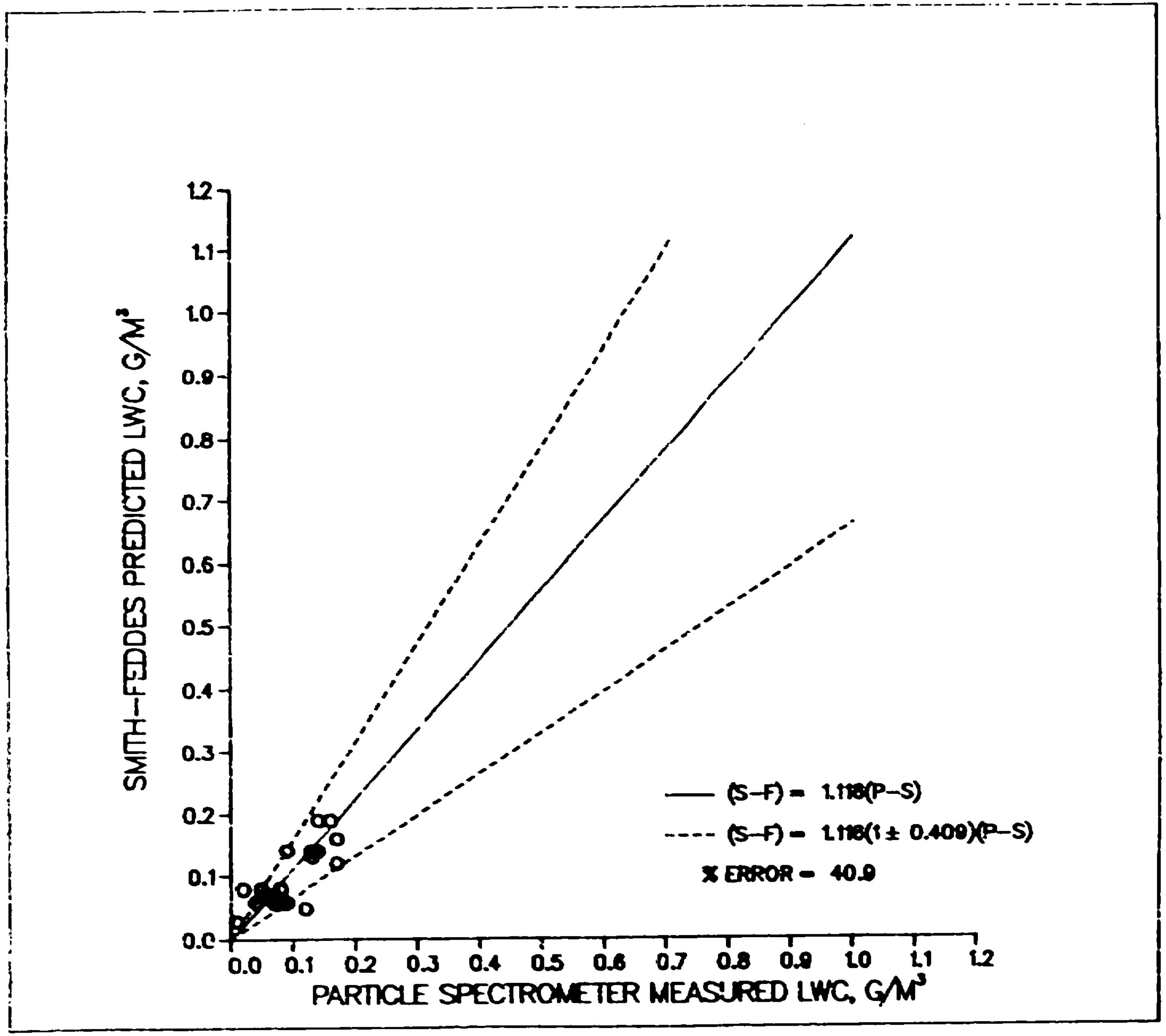

Figure 3.6 P-S Measured LWC vs. S-F Predicted LWC for Stratus Clouds.

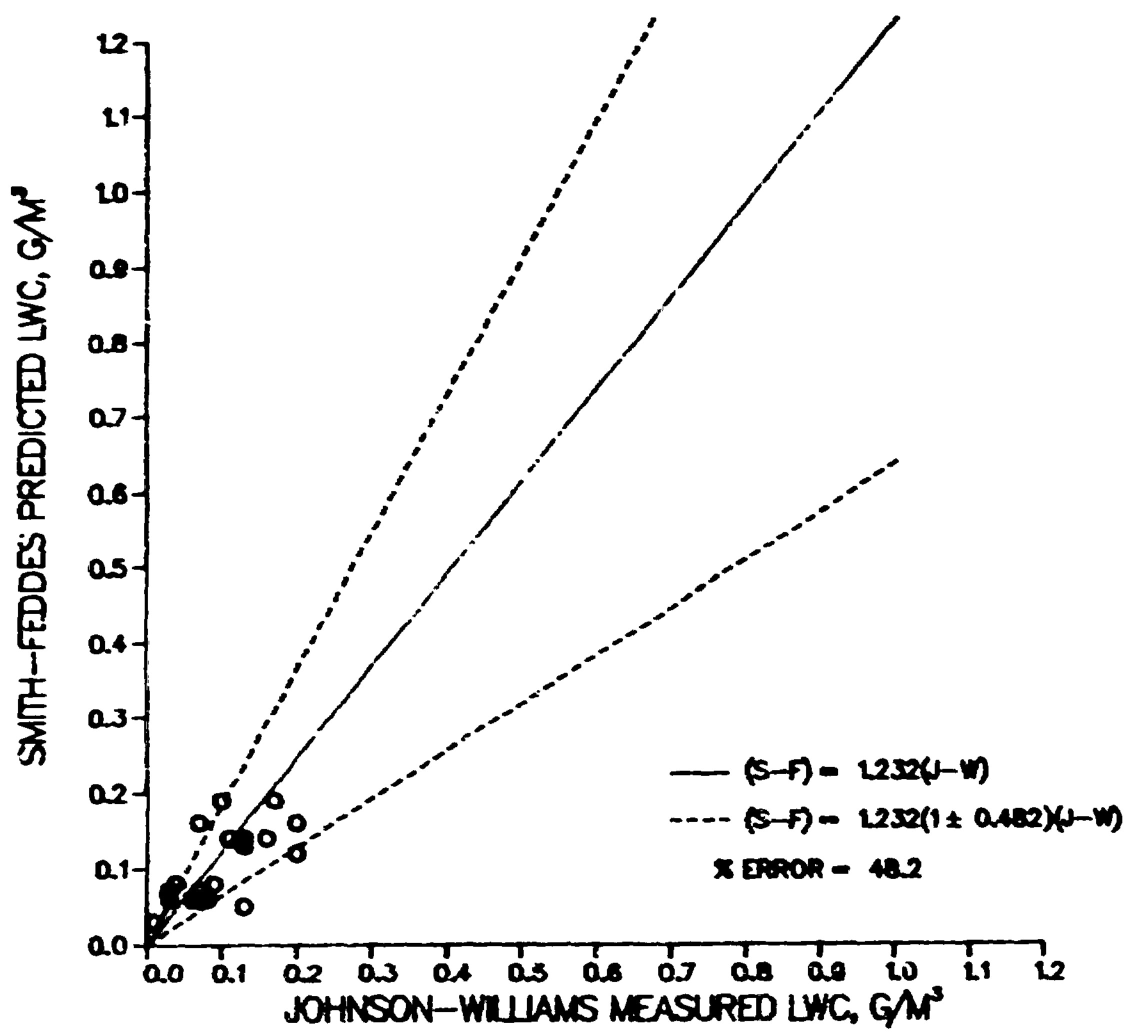

Figure 3.7 J-W Measured LWC vs. S-F Predicted LWC for Stratus Clouds.

comparison, the Smith-Feddes calculated values agree slightly better with the particle spectrometer.

Figures 3.8 and 3.9 show the LWC comparisons for the PS and the JW for stratocumulus (Sc) clouds. The model continues to agree more closely to the particle spectrometer and for Sc the agreement is particularly good even for higher LWC values. Most of the comparison values are for observed values below $0.3 gm/m^3$ so it would be useful to have additional Sc measurements where LWC was greater than $0.3 gm/m^3$.

Figures 3.10 and 3.11 show the LWC comparisons for the PS and the JW for cumulus (Cu) clouds. The percent errors are intermediate between those for stratus and those for stratocumulus and the comparison between the JW and the model calculation is slightly better than for the PS. Most of the LWC comparison which lie significantly outside the percent error lines occur for cumulus. There is an additional factor for cumulus which has not been previously mentioned. In environmental wind shear new growth of cumulus clouds occurs on the upshear side of the cloud, while the downshear side consists mainly of dissipating cloud (Rogers et al. 1985). As a result the maximum LWC values occur on the upwind side of the cloud and gradually diminish downwind. For more complex shear scenarios the maximum LWC center will be shifted offcenter. An aircraft may not adequately sample a cumulus formed in wind shear because of the direction in which the aircraft penetrates the cloud. An along shear path is more likely to faithfully portray the cloud LWC as opposed to an across shear path which has little chance of giving the true cloud averaged LWC. Cumuliform LWC structures and aircraft penetration trajectories would appear to be a factor influencing the model and observation comparisons, which are impossible to account for.

Figures 3.12 and 3.13 show the LWC comparisons for respectively the PS and for the JW for non-convective (stratus, stratocumulus, and altocumulus) clouds. The comparison to the

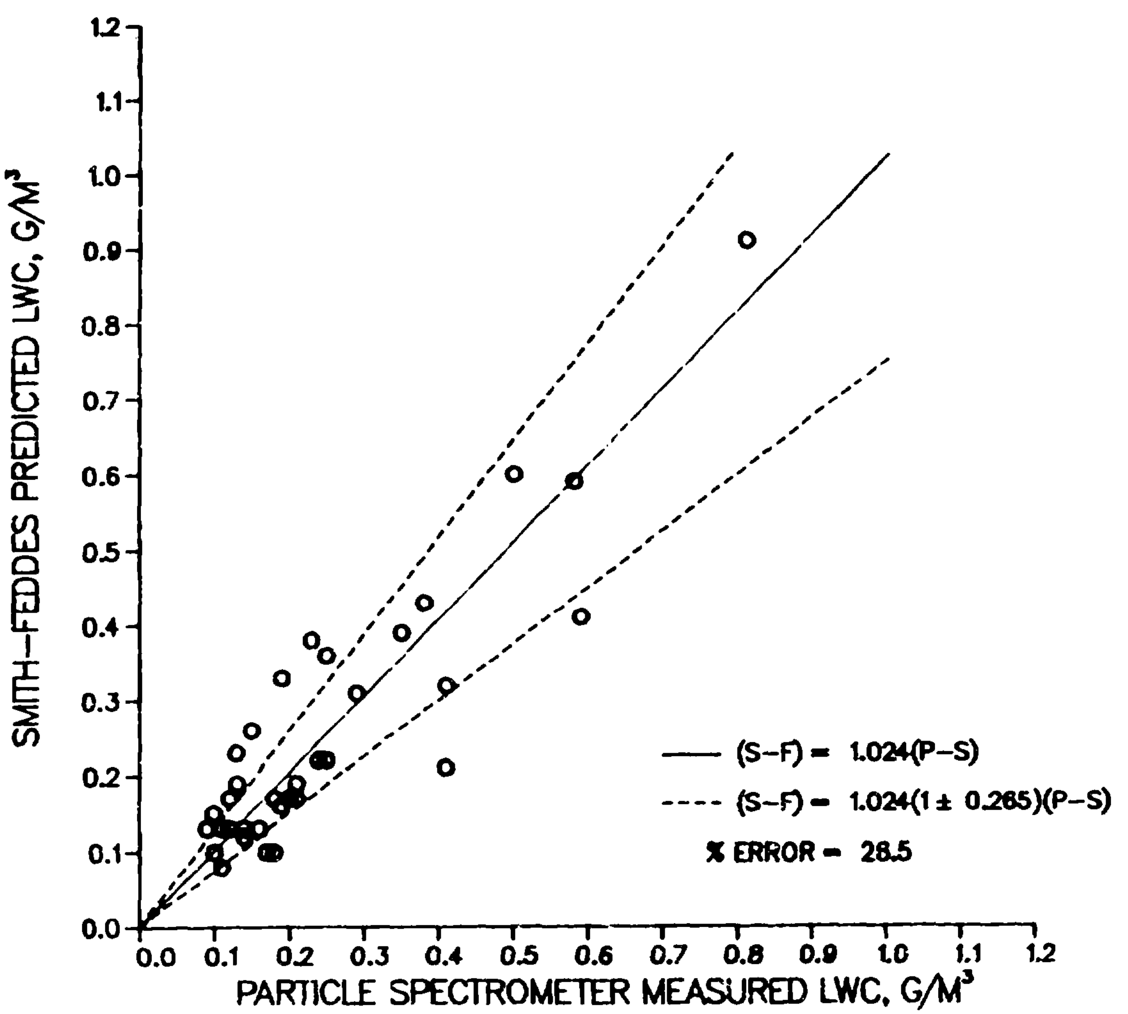

Figure 3.8 P-S Measured LWC vs. S-F Predicted LWC for Stratuscumulus Clouds.

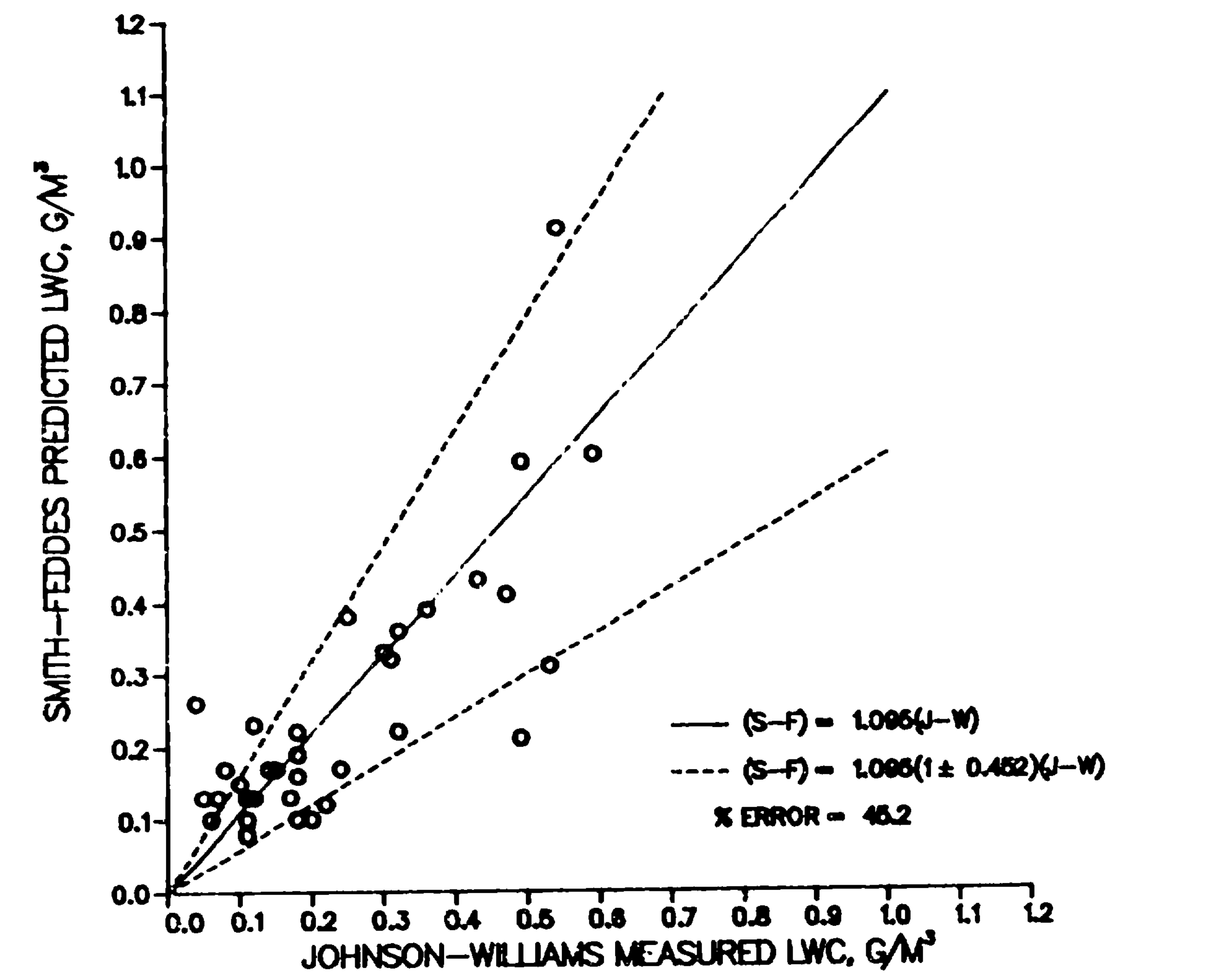

Figure 3.9 J-W Measured LWC vs. S-F Predicted LWC for Stratocumulus Clouds.

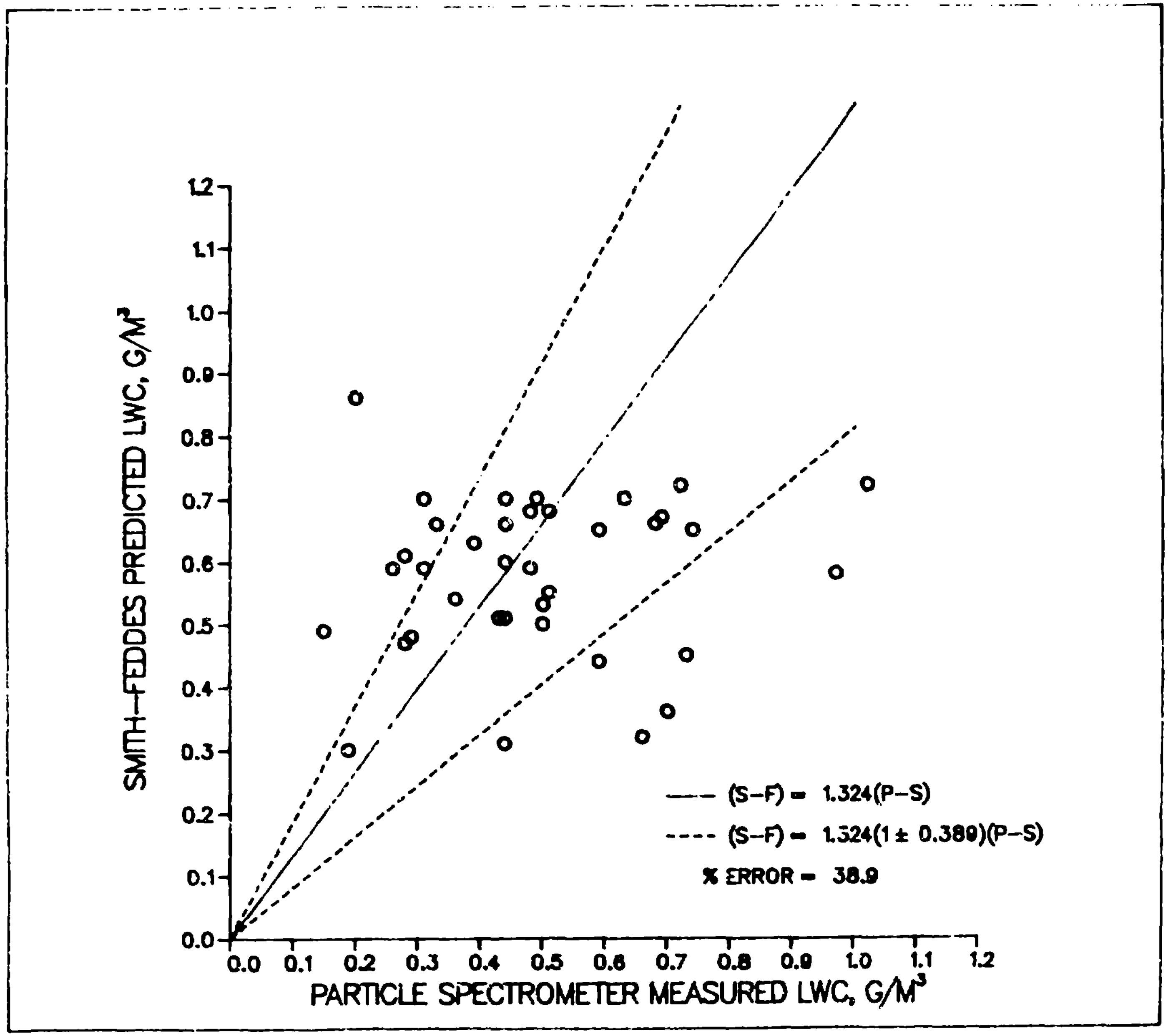

Figure 3.10 P-S Measured LWC vs. S-F Predicted LWC for Cumulus Clouds.

SECTION 4
CONCLUSIONS

The work and research performed as part of this contract was a logical extension of the work and research performed previously by the FAA and NRL in determining the character of the atmosphere with regard to the icing of aircraft. The three parts of the work: collection of foreign data, determining the geographical areas where icing would be prevalent, and finally to develop a data collection scheme without aircraft support provided a logical framework to develop a useful scheme.

4.1 DATA BASE

The collection of foreign icing data was not as fruitful as one would have hoped. There were many disappointments and frustrations. The English in both their meteorological and defense department have data which would have proved useful for the FAA/NRL data base. However, due to events beyond our control, the data was not available to us. However, we did manage to obtain data from the University of Manchester which was tower data including ground fog. The Germans have data from aircraft but would only send us a summary of that data (see Table 1.2). The Russians also have data but no contact was made with them. Those are the negative aspects of the data collection effort. On the positive side, we obtained a large amount of data from the Alberta Research Council in Edmonton, Alberta and from the Atmospheric Environmental Services located in Ottawa. Both of these agencies perform cloud seeding experiments on a somewhat steady plan and have great experience and expertise in the collection of microphysical data of clouds. Data obtained from the JTD Environmental Services Inc. from flights over the North Sea and European countries is also very valid data. Data from the French and South Africa is precisely the same type data as is currently in the FAA/NRL data base, so that data will be useful. Finally the data from Manchester is unique in that it is tower data, including ground fog.

We included all countries in our initial request for data so that each country is aware of the FAA's program in icing data.

The inclusion of this newly acquired non-conus data into the present FAA/NRL will result in a data base that will have data principally from measurements made in Europe and North America along with data from South Africa and thus will be considerably geographically more diverse than before. Though many of the measurements were made in the Northern Hemisphere's severe icing environment, Section 2 suggests that areas of high frequency occurrence of severe icing were not penetrated. Because these areas have moderately heavy air traffic, we recommend that consideration be given for either making additional flight measurements or implementation of the data collection scheme discussed in Section 3.

Further, some [illegible] types such as altostratus (As), altocumulus (Ac), and nimbostratus (Ns) appear to be under-represented in the new data base. The few modern measurements made by the Air Force Geophysics Laboratory show fairly respectable LWC values (up to .4 gm/m^3) for As and Ac so inclusion of more As and Ac measurements into the data base appears desirable. As and Ac associated with strong warm fronts could present horizontally extensive regions of relatively high LWC. This type of weather occurs often in the mid-latitude westerlies during the winter.

Most of the highest LWC values in the new data base occur within convective clouds over the Sierra Nevada range and over northern Spain. However, all measurements were taken in winter and spring months, and since both of these areas are not noted for deep convection it is very desirable to incorporate more warm season deep convection measurements. An encouraging sign is the recent incorporation of Cooperative Convective Precipitation Experiment (CCOPE) data, but more measurements such as those appearing in the South African and Canadian data are needed.

4.2 THE ETAC LWC DATA BASE

The processing of the ETAC LWC (Section 2) data base shows that certain areas in Asia, Europe, and North American are prone to severe icing. Figure 2.11 shows that these areas are not well represented by aircraft measurements so any characterization of the world-wide icing environment based upon measurements may be too lenient. This is especially true for eastern Asia and northern Europe.

It is obviously apparent that aircraft measurement of all areas suspected of having severe icing is both economically impossible and time consuming. In this modern era of satellite probes and high speed computers a better data collection scheme can be devised.

4.3 ALTERNATE DATA COLLECTION SCHEME

Based upon a review of candidate modeling and remote sensing techniques, we conclude that the updated Smith-Feddes model as discussed in Section 3 offers the best hope for an alternative data development scheme to enhance the new data base. As shown in Section 3 the updated Smith-Feddes model gives a reliable predictio of LWC and temperature but poor predictions of the total drop spectrum. We have proposed but not implemented a method to improve this.

We also know that geographical location, in cloud position, cloud age and interaction between clouds are important factors influencing the drop size distribution. We believe that at least geography and in cloud position could be incorporated into the SFM to yield drop size distributions. These improvements would address the variation of Cloud Condensation Nuclei (CCN) particularly between oceanic and continental regions and the shift of the drop spectrum to higher radii with height in clouds. These improvements could be incorporated in a relatively simple manner and validated against the data base as in Section 3.

4.4 CONCLUSIONS

The results of this work have been to add data to the existing data bank, to show that some areas with good potential for hazardous icing conditions have not been subjected to aircraft measurements, and finally that it is possible to predict icing conditions to a fair amount of reality, thus obviating the need for costly and time consuming aircraft measurements.

SECTION 5

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APPENDIX A

This appendix lists all agencies to which the inquiry letter concerning icing data was sent.

The response to the inquiry letter is indicated in the response line by either (1) a "no response" meaning just that, (2) a "no data" indicating that a letter was received from the agency stating that the agency had no data but with no further information, or (3) a letter was received with information which is summarized in the response line.

BELGIUM (Continued)

04-03
Association Belge des Pilotes
et Navigateurs de Ligne (ABPNL)
Avenue Henri Dunant 2,
1140 Bruxelles
BELGIUM
(02) 36 02 64
FIRST LETTER SENT: 850712
RESPONSE: No data

04-04
Association Belge des Journalistes
Professionnels de l'Aeronautique et
de l'Astronautique (ABJPAA)
Square de l'Arbalete 4
1170 Bruxelles
BELGIUM
(02) 73 24 06
FIRST LETTER SENT: 850712
RESPONSE: No data

04-05
Mr. J. Ooms
A.B.I.
Openlucht Wandelgang 48
B 1150 St. Pieters-Woluwe
BELGIUM
FIRST LETTER SENT: 850813
RESPONSE: No data

04-06
Mr. DeRidder
Director Meter
Regie der Luchtwegen
Brussels National Airport
B 1930 Zeventam
BELGIUM
FIRST LETTER SENT: 850813
RESPONSE: No data

BELGIUM (Continued)

04-12
Mr. Homble
SABENA
Service Formation and Qualification
Brussels National Airport
B1930 Zaventem
BELGIUM
011 32 2 720 59 80, ext. 3966
FIRST LETTER SENT: 850916
RESPONSE: No Response

04-13
Mr. G. Doumont
Directeur d'Administration,
R.V.A.
Centre de Communications Nord,
Rue du Progres, 84bis, bte 1
1000 Bruxelles
BELGIUM
FIRST LETTER SENT: 851002
RESPONSE: No response

CANADA (General)

05-01
Dr. Larking Kerwin
National Research Council of Canada
Montreal Road
Ottawa, Ontario
CANADA K1A 0R6
(613) 993-9109 (NRC)/(613) 933-2371 (Stallabrass)
FIRST LETTER SENT: *,850712(cc. Stallabrass)
RESPONSE: No data

05-02
Dr. Ed Lozowski
University of Alberta
Edmonton, Alberta
CANADA T6G 2E8
(403) 432-2325 (Univ.)
FIRST LETTER SENT: *,850712
RESPONSE: Referred us to Dr. R. Humphries of the Alberta Research Council. See 05-05

CANADA (Continued)

05-07
Dr. Robert S. Schemenauer
Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario
CANADA M3H 5T4
(416) 667-4683
FIRST LETTER SENT: *,850712
RESPONSE: The AES sent data from six projects.

05-08
Public Information Officer
International Civil Aviation
Organization (ICAO)
International Aviation Square
1000 Sherbrooke St. W.
Montreal, Quebec
CANADA H3A 2R2
(514) 285-8220
FIRST LETTER SENT: 850712
RESPONSE: No data, but recommended a Swedish contact.

05-09
P. A. Corbett, Exec. Sec.
Canadian Aeronautics and
Space Institute
#60 75 Sparks Street
Ottawa, Ontario
CANADA K1P 5A5
(613) 234-0191
FIRST LETTER SENT: 850712
RESPONSE: No response

05-10
Mr. Roger Burgess-Webb
Manager, Information Services
Canadian Air Line Pilots Association
1300 Steeles Ave. E.
Brampton, Ontario
CANADA L6T 1A2
(416) 452-8210
FIRST LETTER SENT: 850712
RESPONSE: No response

CANADA (Continued)

05-15
Mr. Ken Grandia
Alberta Research Council
Atmospheric-Sciences Department
7th Floor, Terrace Plaza
4445 Calgary Trail South
Edmonton, Alberta
CANADA T6H 5R7
FIRST LETTER SENT: 850901
RESPONSE: See 05-05

CANADA (AES)

06-01
Atmospheric Environmental Service
4905 Dufferin St.
Downsview, Ontario
CANADA M3H 5T4
(416) 667-4551
FIRST LETTER SENT: 850712
RESPONSE: See 05-06 and 05-07

06-02
Dr. A. D. J. O'Neill
Director, Atlantic Office
Atmospheric Environmental Service
1496 Bedford Hwy
Bedford, Nova Scotia
CANADA B4A 1E5
(902) 835-9328
FIRST LETTER SENT: 850712
RESPONSE: See 05-06 and 05-07

06-03
R. J. Fichaud
Director, Quebec Office
Atmospheric Environmenatl Service
100 Alexis Nichon Blvd - 3rd Floor
Ville St. Laurent, Quebec
CANADA H4M 2N6
(514) 333-3000
FIRST LETTER SENT: 850712
RESPONSE: See 05-06 and 05-07

Canada (Continued)

06-08
F. J. Lemire
Canadian Meteorological Centre
2121 N. Service Rd. #404
Trans Canada Hwy
Dorval, QC
CANADA H9P 1J3
(514) 683-7274
FIRST LETTER SENT: 850712
RESPONSE: No reply

CARIBBEAN

07-01
Caribbean Meteorological Institute
P. O. Box 130
Bridgetown
BARBADOS
1-809-425-1362
FIRST LETTER SENT: 850712
RESPONSE: No data

07-02
The Coordinating Director
Caribbean Meteorological Org. (CMO)
P. O. Box 461
Port-of-Spain
TRINIDAD-TOBAGO
1-809-624-3121
FIRST LETTER SENT: 850712
RESPONSE: No data

07-03
The Director
Meteorological Services
Grantley Adams International Airport
Christ Church
BARBADOS
809-428-8521
FIRST LETTER SENT: 850801
RESPONSE: No data

FRANCE

11-01
Mr. Martin Friedlander
Centre d'Assais en Vol (CEV) - France
French Military Testing/Flight Test Ctr.
91220 Burt( )ton Brittany-Fur-Orde,
FRANCE
011 33 6084 9570 Ext 3242
011 33 6171 0249
FIRST LETTER SENT: *,850712
RESPONSE: They sponsor Dr. Gayet

11-02
Mr. J. F. (Jean-Francois) Gayet
Laboratoire Associe de
Meteorologie Physique
Universite of Clermont II
B.P. 45, 63170 Aubiere,
FRANCE
FIRST LETTER SENT: *,850712
RESPONSE: Sent data in the fall of 86.

11-03
Prof. R. G. Soulage
Universite de Clermont II
63170 Aubiere
FRANCE
FIRST LETTER SENT: *,850712
RESPONSE: He is Dr. Gayet's supervisor.

11-04
Madam H. Bouilloud
Ministry of Defense
STPA/CIN
4 Avenue Delaporte d'essy
75996 Paris Armees
FRANCE
1 552 5319
FIRST LETTER SENT: 850712
RESPONSE: They sponsor Dr. Gayet

FRANCE (Continued)

11-10
Meteorologie Nationale
Respondeur Renseignements lie de
France et·Normandie
2 av Rapp 7
Paris,
FRANCE
(1) 555.95.90
FIRST LETTER SENT: 850712
RESPONSE: No response

11-11
Mission des etudes et de la recherche
14, boulevard du General Leclerc
92524 Neuilley-sur-Seine Cedex
Paris,
FRANCE
(1) 758.12.12
FIRST LETTER SENT: 850712
RESPONSE: No response

11-12
Centre national de la
recherche scientifique
15, quai Anatale France 7
Paris,
FRANCE
(1) 555.92.25
FIRST LETTER SENT: 850712
RESPONSE: No response

GERMANY

12-01
Dr. Hans Eberhard Hoffmann
Institute of Atmospheric Physics
(Institut fur Physik der Atmosphare)
Deutsche Forschungs- und Versuchanstalt
fur Luft- und Raumfahrt (DFVLR)
Oberpfaffenhofen D-8031
8031 Wessling
GERMANY FR
011 4981 5328 Ext 579 (081 53/28-579)
FIRST LETTER SENT: 850712
RESPONSE: Dr. Hoffmann has sent us summaries of his data. For reasons not clear to UDRI, he did not send UDRI the magnetic tape data.

Germany (Continued)

12-06
Mr. Peter Schramm
German Defense Test Center
or German Experimental Center
(Bondeswehr Erprobungsstelle)
Erprobungsstelle, 61 der Bundeswehr
Dezernat 234 Flugplatz,
8072 Manching
WEST GERMANY
08459-802174
FIRST LETTER SENT: 850712
RESPONSE: See 12-01

12-07
Mr. Kurt Uwira
German Defense Test Center
or German Experimental Center
(Bondeswehr Erprobungsstelle)
Bundesamt fur Wehrtechnik und
Beschaffung AFB LG III
Flugplatz
8072 Manching
WEST GERMANY
FIRST LETTER SENT: 850712
RESPONSE: See 12-01

12-08
Herr Richter
German Defense Test Center
or German Experimental Center
Bundesamt fur Wehrtechnik und Beshaffing
Erprobungsstelle, 61 der Bundeswehr
8072 Manching
WEST GERMANY
FIRST LETTER SENT: 850712(copy of 12-06)
RESPONSE: See 12-01

12-09
Mr. Eckert
German Defense Test Center
or German Experimental Center
Bundeminister fur Verteidigung
RU IV 6, F. Hel Hern Eckert
53 Bonn
WEST GERMANY
FIRST LETTER SENT: 850712(copy of 12-06)
RESPONSE: See 12-01

ITALY

15-01
Associazione Industrie Aerospaziali
via Naziovale 200
Roma,
ITALY
(06) 46 02 47
FIRST LETTER SENT: 850712
RESPONSE: No response

15-02
AOPA Italia
Organizzozione dell 'Aviazione
Private e d'Affari
Corso Magenta 56,
20123 Milano,
ITALY
(02) 87 38 02
FIRST LETTER SENT: 850712
RESPONSE: No response

15-03
Associazione Nazionale Piloti
Aviazione Commerciale (ANPAC)
Viale dell'Esperanto 71
00144 Roma
ITALY
(06) 591 04 11
FIRST LETTER SENT: 850712
RESPONSE: No response

15-04
Associazione Nazionale Piloti
Aviazione Generale (ANPAG)
Via Mamiani 15/2
20127 Milano
ITALY
(02) 289 60 59
FIRST LETTER SENT: 850712
RESPONSE: No response

15-05
Unione Giornalisti Aeronautici Italini
Corso Trieste 10
00198 Roma
ITALY
(06) 85 51 71
FIRST LETTER SENT: 850712
RESPONSE: No response

THE NETHERLANDS

19-02
Prins Maurits Lab., TNO
(Dutch Org. for Applied Research)
Lande Kleiweg 137
228 GJ Rijswijk
THE NETHERLANDS
FIRST LETTER SENT: 850712
RESPONSE: Sent letter to the Dutch National Air and Space Laboratory who in turn sent it to Fokker Aircraft. See 19-08 of this Appendix.

19-03
AOPA Netherlands
Jozef Israelsplein 8
Den Haag
THE NETHERLANDS
FIRST LETTER SENT: 850712
RESPONSE: No response

19-04
Vereniging van Nederlandse Verkeersvliegers (VNV)
Dutch Airline Pilots Association
Amsterdamseweg 138
Amstelveen,
THE NETHERLANDS
(020) 41 05 55
FIRST LETTER SENT: 850712
RESPONSE: No response

19-05
Nederlandse Vereniging van Lucht- en Ruimtevaart- Publicisten (NVLP)
Jozef Israelsplein 8
Den Haag
THE NETHERLANDS
(070) 24 72 52
FIRST LETTER SENT: 850712
RESPONSE: No response

19-06
Dr. E. Hosstee
Meteo Amsterdam Airport
THE NETHERLANDS
FIRST LETTER SENT: 850712
RESPONSE: No response

PORTUGAL

22-01
Sindicato Nacional de Pessoal
de Voo da Aviacao Civil (SNPVAC)
Praca Pasteur 11
R/C-D, Lisboa
PORTUGAL
72 87 74
FIRST LETTER SENT: 850712
RESPONSE: No response

SCOTLAND

23-01
Scottish Meteorological Society
Edinburgh,
SCOTLAND
FIRST LETTER SENT: 850712
RESPONSE: No response

SOUTH AFRICA

24-01
Roelof Bruintjes
South African Weather Bureau
P. O. Box 169
Irene, 1675
REPUBLIC OF SOUTH AFRICA
011-27-12-290-000 (6 hours ahead of U.S.)
FIRST LETTER SENT: *,850712
RESPONSE: Received two magnetic tapes of data.

24-02
Council for Scientific and Industrial
Research (CSIR)
CSIR/WNNR
Attn: Cloud Physics Group
Pretoria,
REPUBLIC OF SOUTH AFRICA
FIRST LETTER SENT: 850712
RESPONSE: Suggested 24-03, 24-04, and 24-05

SPAIN (Continued)

25-02
Agrupacion Sindical de
  Pilotes de Lineas Aereas (ASPLA)
Paseo del Prado 18-20
Planta 5a
Madrid 14
SPAIN
FIRST LETTER SENT: 850712
RESPONSE: No response

SWEDEN

26-02
AOPA Sweden
Svenska Allmanflygforening
Fack, 161 10 Bromma 10
SWEDEN
(08) 29 50 00
FIRST LETTER SENT: 850712
RESPONSE: No data. They also indicated that neither the Swedish Board of Civil Aviation, the Swedish Meteorological and Hydrological Institute, the Stockholm University, the Aeronautical Research Institute of Sweden, nor the Royal Technical High School of Stockholm had any data.

26-03
Svensk Pilotforening (SPF)
Swedish Airline Pilots Association
Olofsgatan 10, 2 tr,
111 36 Stockholm C.
SWEDEN
(08) 10 94 34
FIRST LETTER SENT: 850712
RESPONSE: No response

26-04
John Ogren
University of Stockholm
Dept. of Meteorology/Arrhenius Lab.
S-106 91,
Stockholm,
SWEDEN
011-46-8-162000 (Univ. of Stockholm)
FIRST LETTER SENT: 850712
RESPONSE: No data
Mr. Heintzenberg
RESPONSE: No response

SWITZERLAND (Continued)

27-02
Global Atmospheric Research
Programme (GARP)
GARP Activities Office
c/o WMO
Case Postale 5, CH 1211
Geneve 20,
SWITZERLAND
34 64 00
FIRST LETTER SENT: 850712
RESPONSE: No response

27-03
Vereinigung der Schweizereschen
Fluggeugindustrie
Association Suisse de l'Industrie
Aeronautique (ASIA) Theaterplatz 4,
5400 Baden,
SWITZERLAND
(056) 2 30 90
FIRST LETTER SENT: 850712
RESPONSE: No response

27-04
AOPA Switzerland
P. O. Box 151
8058 Zurich Airport
Zurich,
SWITZERLAND
(051) 84 01 85
FIRST LETTER SENT: 850712
RESPONSE: No data

27-05
Aeropers (Schweiz.)
8152 Glattbrugg,
Rietstrasse 17
SWITZERLAND
FIRST LETTER SENT: 850712
RESPONSE: No response

27-06
Schweizerische Meteorologische Anstalt
Swiss Meteorological Institution
Krahbuhlstrasse 58
CH-8044 Zurich SWITZERLAND
FIRST LETTER SENT: 850807
RESPONSE: No response

UNITED KINGDOM (Continued)

29-04
Dr. J. T. Cansdale
Royal Aircraft Establishment
Farnsborough, Harts.,
ENGLAND
011 44 252 24461 Ext. 2491
FIRST LETTER SENT: *,850712
RESPONSE: Sent letter to A&AEE (29-01)

29-05
G. M. E. White
Secretary
Civil Aviation Authority
CAA House, 45-59 Kingsway
London
UNITED KINGDOM WC2B 6TE
01-379 7311
FIRST LETTER SENT: 850712
RESPONSE: No data

29-07
Frank Atkinson
British Airways Helicopters
Gatwick Airport
Surrey,
ENGLAND
FIRST LETTER SENT: 850712
RESPONSE: No response

29-09
Peter Soliz
Major USAF
Chief, Geophysics and Space
European Office of Aerospace R&D
223/231 Old Marylebone Rd.
London, NW1 5th
ENGLAND
(01) 409-4437 TELEX-299739
FIRST LETTER SENT: 850712
RESPONSE: See 29-01

UNITED KINGDOM (Continued)

29-15
Mr. R. O. Belton, Secretary
Board Air Safety Review Committee
British Airways,
Heathrow Airport
P. O. Box 10
Hounslow,
ENGLAND TW6 2JA
011-44-01-759-5511
FIRST LETTER SENT: 850712
RESPONSE: No data

29-16
Mr. Alan A. Woodfield,
Royal Aircraft Establishment
General Aerodynamics Section,
Flight Research Division
Bedford,
ENGLAND
011-44-234-55241
FIRST LETTER SENT: 850712
RESPONSE: No response

29-17
Capt. R. D. Hillary
Commonwealth Advisory Aeronautical
Research Council (CAARC)
c/o Ministry of Defense
Old War Office Bldg. - Room SW1A
Whitehall, London,
UNITED KINGDOM SW1A 2EU
218 0838
FIRST LETTER SENT: 850712
RESPONSE: No data

29-18
Rolls-Royce Ltd.
65 Buckingham Gate
London, SW1,
UNITED KINGDOM
FIRST LETTER SENT: 850712
RESPONSE: No response

UNITED KINGDOM (Continued)

Agency:

The University of Manchester
Institute of Science and Technology

Contact:

Professor John Latham
The University of Manchester
Institute of Science and Technology
P. O. Box 88
Manchester M60 19D

061-236-3311

RESPONSE: Received five days of data.

USSR

30-01
Prof. I. P. Mazin
Soviet Geophysical Committee
Molodezhnaya 3,
Moscow 117296,
USSR
Not available
FIRST LETTER SENT: 850712
RESPONSE: No response

30-02
The Institute of Atmospheric Physics
University of Moscow
Leninsky Gory
Moscow,
USSR
FIRST LETTER SENT: 850712
RESPONSE: No response

30-03
Dr. Leonid T. Matveev
Leningrad Hydrometeorological Institute
Leningrad
USSR
FIRST LETTER SENT: 831105
RESPONSE: No response

APPENDIX B

The following pages comprise the mailing that was sent to each of the agencies listed in Appendix A.

The University of Dayton

(Date)

(Contact's Name)
(Agency Name)
(Agency Address)

Dear (Contact's name):

The Federal Aviation Administration (FAA) recently completed an aircraft icing data gathering and analysis effort which resulted in a new characterization of the aircraft icing environment in supercooled clouds up to 3 km above ground level for the continental United States. The FAA is now continuing to characterize the aircraft icing atmosphere for all conditions and for all altitudes both in the U.S.A. and worldwide in a planned sequence.

The Icing data base is being developed and maintained at the U.S. Naval Research Laboratory under the direction of Dr. Richard Jeck of NRL and sponsored by the FAA.

The role of UDRI as explained in the cover letter is to establish contact with governments and scientific groups outside the U.S.A. and arrange for the retrieval of pertinent aircraft icing data so that when added to the already existing continental U.S.A. icing data base, a truly world-wide data base will be available to all participating countries.

We are interested in retrieving the following types of data which we have labeled Primary, Secondary, and Supplementary.

<u>Primary Data</u> (Required to characterize the icing environment)

Simultaneous measurements in ground fog or in/beneath clouds containing any supercooled water droplets including freezing precipitation or ice crystals including snow, or combinations thereof, of the following variables:

RESEARCH INSTITUTE
Applied Systems Analysis
300 College Park Dayton, Ohio 45469-0001

Variable	
Liquid Water Content (or equivalent)	- redundant measurements preferred
Droplet Median Volume Diameter	
Air Temperature	- corrected preferred
Aircraft Altitude	- pressure altitude and above ground level preferred
Aircraft True Airspeed	
Time/Duration/Distance of Icing Event	

Secondary Data

Secondary data is desirable but not necessary.

Variable	
Droplet Size Spectra	- distribution
Droplet Concentration	- number density
Aircraft Location	- geographic
Aircraft Attitude	- climb, level flight, descent, etc.
Terrain Height	- mean sea level elevation

Supplementary Information

Supplementary information is highly desirable.

Technical reports on data analysis or case studies.
Summary reports on flight operation or field projects.
Scientific observation notes or flight logs from pilot or onboard scientist, especially information on cloud conditions, icing conditions, precipitation type and intensity, instrument performance.
Information on data quality, error correction procedures.

Note: Preferred data medium is digital computer tapes with documented format.

With this information in mind we would like to ask you the following:

1. Do any of the above mentioned kinds of data exist at your agency?

2. If so, is it possible for UDRI to obtain the data for the FAA?

3. If the data does exist, in what form does it exist, i.e., magnetic tape, reports, computer printout, etc. (Please be as specific as possible) and is it possible to send samples of the data?

4. Would it be possible for you to send us a list of airborne cloud physics field projects over the past ten years and a list of references to related technical reports (published or internal), conference papers, and published scientific articles, that your agency has been involved in?

5. Could you recommend other places to inquire among universities, military, and government agencies, either in your country or others?

6. Could you furnish us with the name(s) of the proper person(s) to contact on this matter and their correct address and phone number?

The UDRI and the FAA both recognize and appreciate any efforts you may be able to extend to us. The FAA has already stated that they consider the creation of this world-wide data base to be an international effort and as such are willing to share the completed data base with all participants.

Thank you for your time and consideration in this important endeavor.

With best regards,

N. A. Engler

Nicholas A. Engler
Senior Research Physicist

NAE/gw

U.S. Department of Transportation
Federal Aviation Administration

Technical Center

Atlantic City Airport
New Jersey 08405

To whom it may concern:

The University of Dayton is currently under contract with the Federal Aviation Administration (FAA), to conduct a research effort to better define the atmospheric parameters conducive to the formation of in-flight icing on aircraft. The results of the effort will be used to aid in the design of aircraft anti-icing and deicing equipment.

The University of Dayton, intends to contact various foreign cloud physics groups and other related activities, concerning information on this matter. Your cooperation with the University of Dayton is greatly appreciated.

Sincerely,

Donna C. Land

Donna C. Land
FAA Contracting Officer

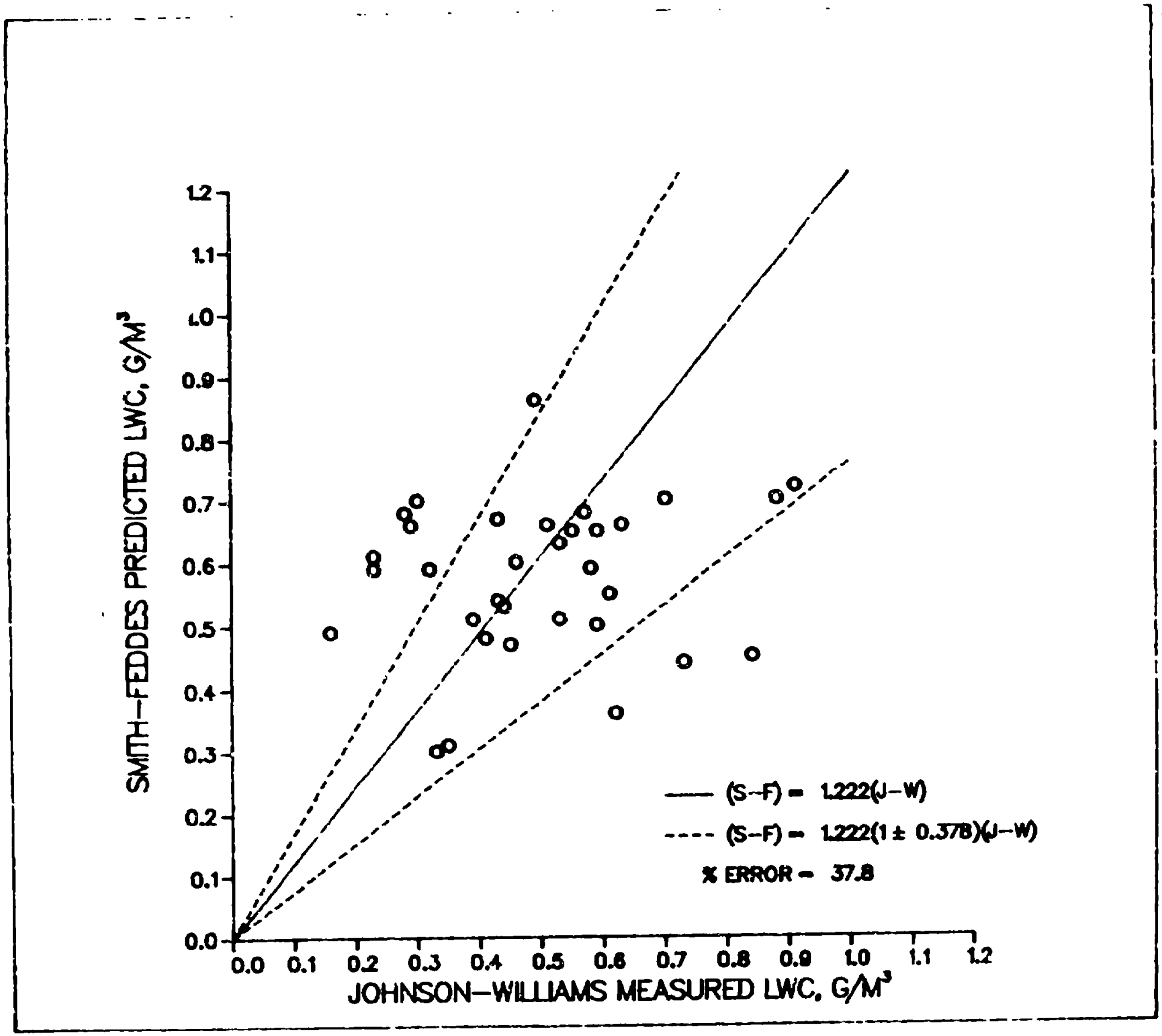

Figure 3.11 J-W Measured LWC vs. S-F Predicted LWC for Cumulus Clouds.

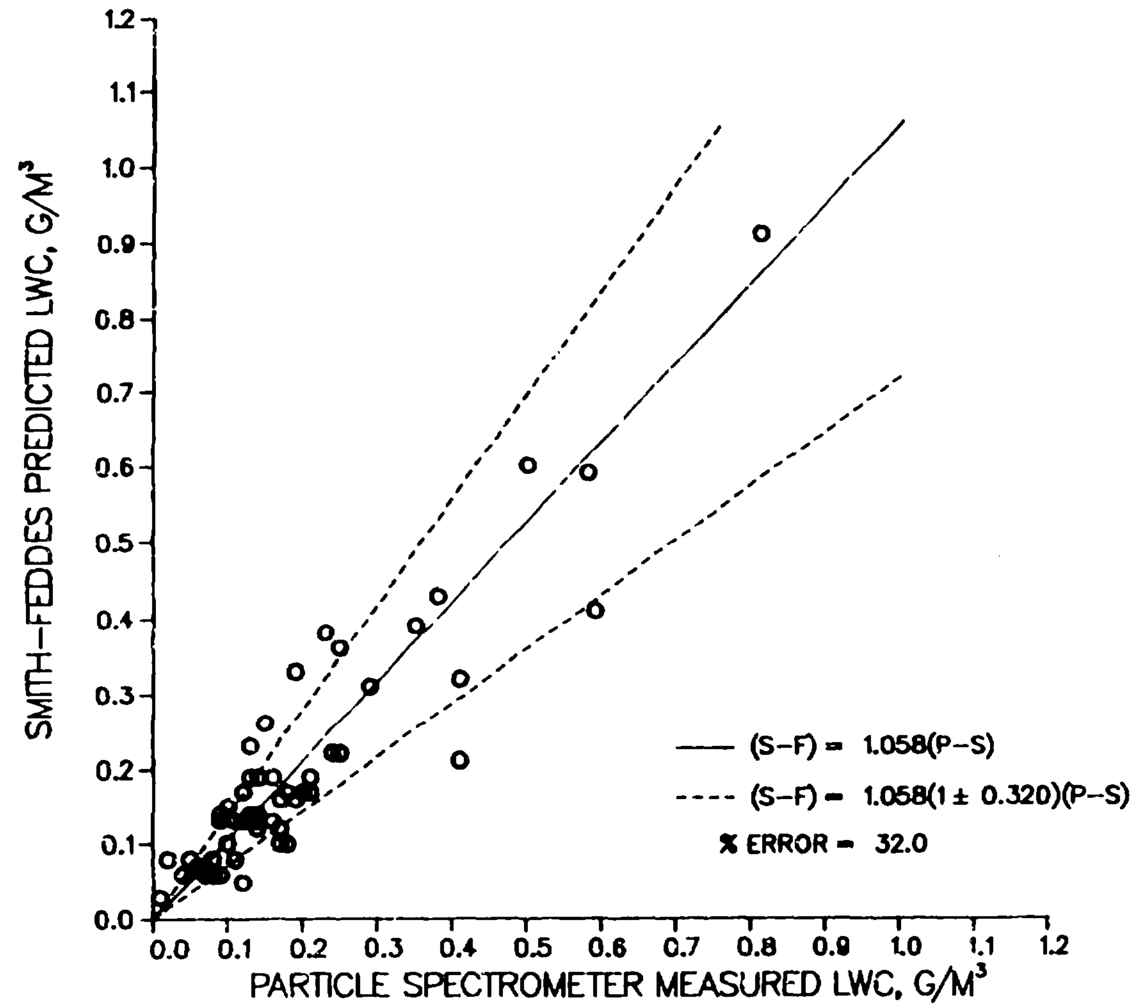

Figure 3.12 P-S Measured LWC vs. S-F Predicted LWC for ST, SC, and AC Cloud Types.

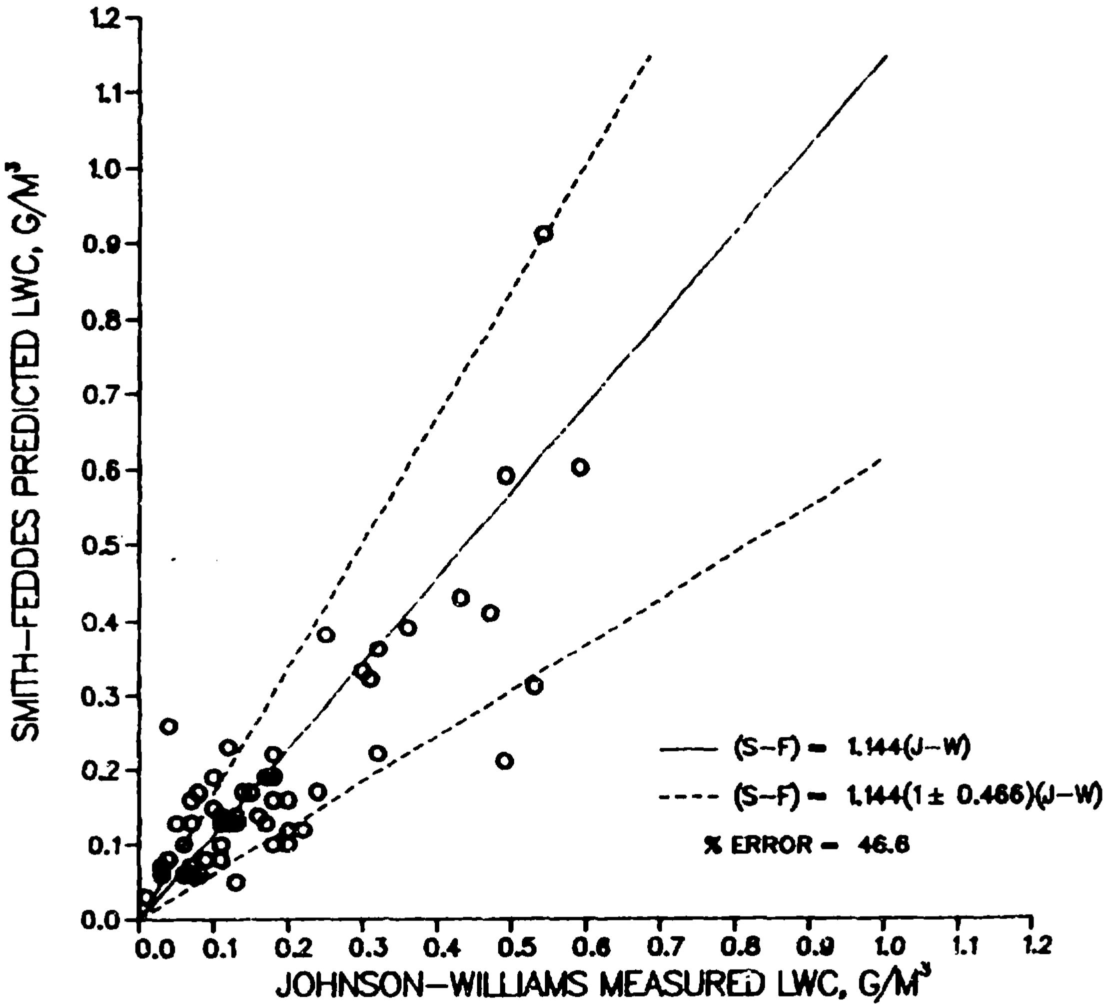

Figure 3.13 J-W Measured LWC vs. S-F Predicted LWC for ST, SC, and AC Cloud Types.

particle spectrometer is particularly good, we note that the comparison continues to be good even for higher LWC values (admittedly too few).

Finally Figures 3.14 and 3.15 show the LWC comparisons between the JW and the PS for respectively non-convective and convective clouds. The percent error for non-convective clouds is greater than that for the comparison between the PS and the Smith-Feddes model. It is interesting that the LWC measurements for cumulus have a smaller percent error between the two devices than between the model and the LWC measurement devices. It is tempting to speculate that the percent error is relatively larger for smaller LWC values and is expected to decrease with increasing LWC. Some of the discrepancy between the model and measurements can be attributed to the sampling strategy.

3.5 CONCLUSIONS FROM THE VALIDATION STUDY

(1) The model compares slightly better to the particle spectrometer than to the Johnson-Williams probe.

(2) The model's percent error is about the same for all types of clouds, perhaps slightly better for Cu than for other types of clouds.

(3) The model's predictive error is no worse than the measuring devices' error.

(4) Even with an approximate 40% error, the uncertainty in the icing severity is minimal. For example, given a moderate to severe icing condition, which has a mean volume drop diameter of 15 microns, and a LWC of 1 gm/m^3, the 40% uncertainty would produce a LWC range of 0.6 (moderate) to 1.4 gm/m^3 (severe) icing condition.

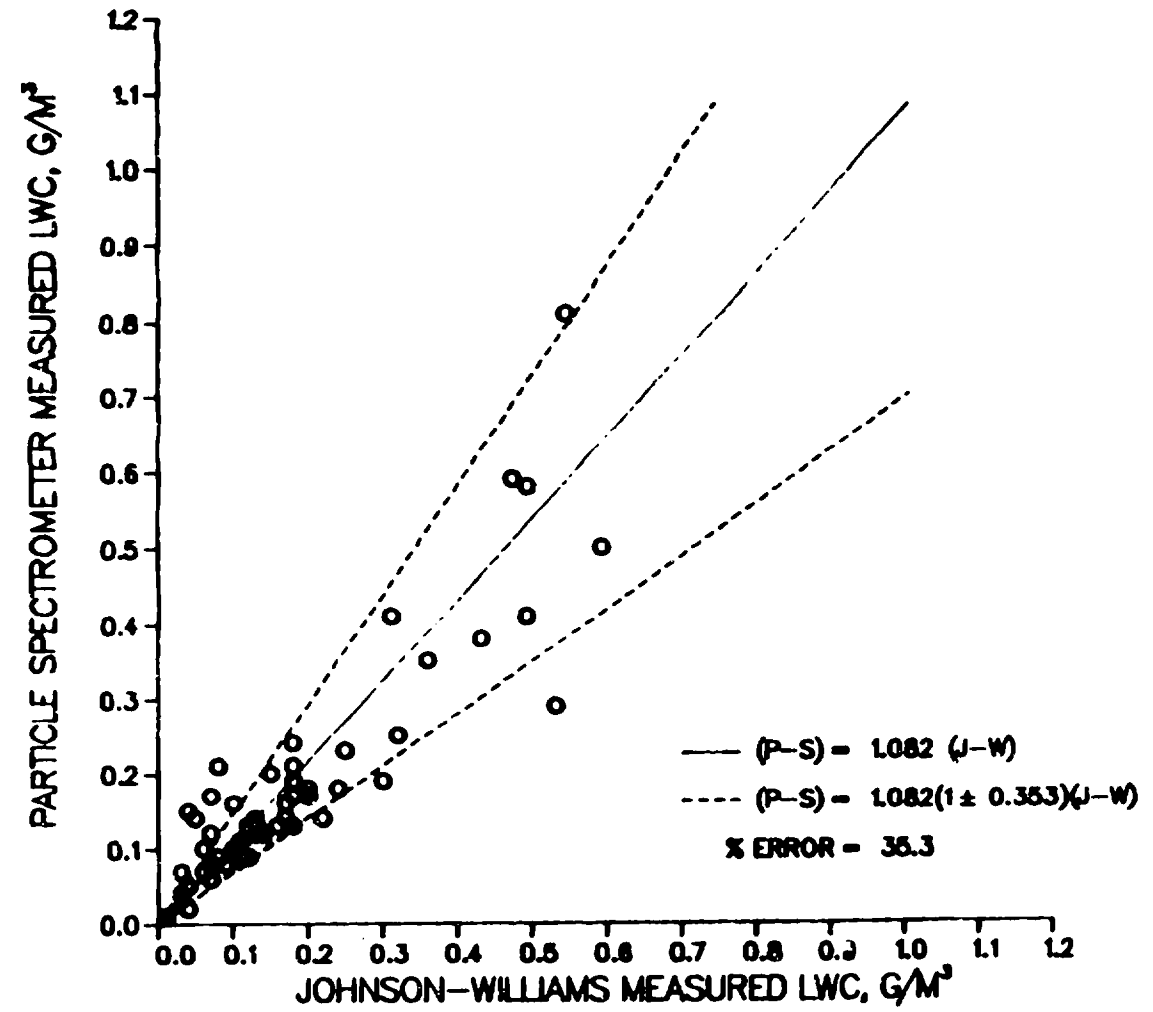

Figure 3.14 J-W Measured LWC vs. P-S Measured LWC for ST, SC, and AC Cloud Types.

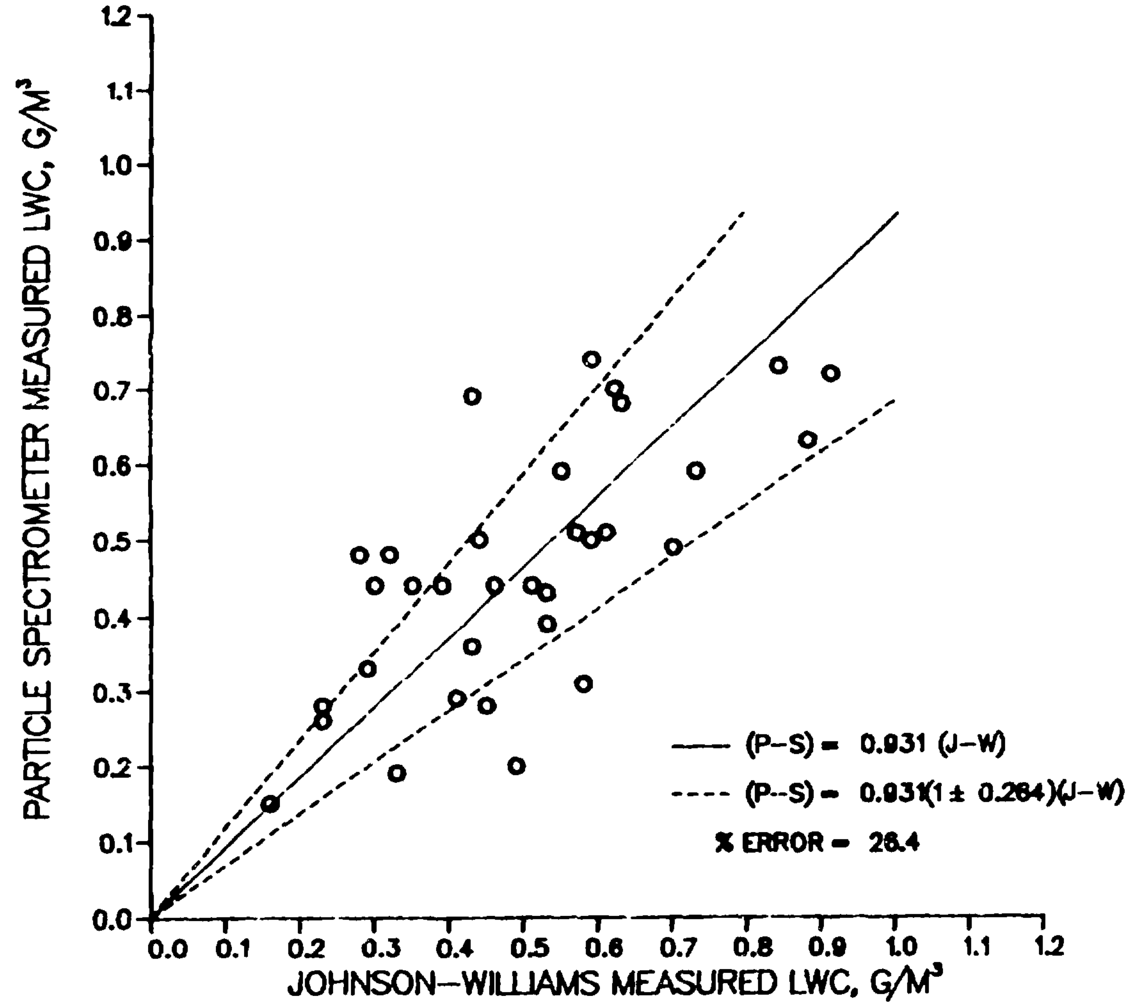

Figure 3.15 J-W Measured LWC vs. P-S Measured LWC for Cumulus Clouds.

3.6 APPLICATION OF THE SMITH-FEDDES MODEL TO ALTERNATE DATA DEVELOPMENT

With improvements to the drop size calculation as mentioned above, the modified updated Smith-Feddes model satisfies the criteria for an alternate data development scheme i.e., it gives useful values of at least LWC and temperature and reasonable values of MVD. In fact, the agreement of JW and PS measurements is not appreciably better than for the measurements and the model calculations. With such a tool available, the question becomes one of use; how should this version of the Smith-Feddes model be used to generate additional data to extend the validity of the FAA/NRL data base? We envision two possible strategies to do this. One strategy is to make a statistically significant number of Smith-Feddes calculations for data sparse regions where the icing environment has been identified as severe (Section 2). The second strategy is to make a parametric study by varying the model's input and then to assess the climatological likelihood of input conditions that predict severe icing.

Under the first strategy, the Smith-Feddes model would be run for a large number of data inputs. The data would arise from RTNEPH and AFGWC temperature and height analyses for the geographical regions identified in Section 2 as prone to severe icing. A major question is the quality of the RTNEPH analysis for the regions identified in Section 2 as well as the vertical resolution of temperature and height analyses. A final question is how many runs are enough? Perhaps the guidelines set forth by Jeck (1983) for data miles for various weather conditions can be adapted to the alternate data application. Otherwise we could use one year's data of twice per day observations.

For the second strategy, a parametric variation of Smith-Feddes input over conceivable ranges would give a number of output scenarios. It would only be necessary to consider those scenarios that predict severe icing. We would then establish the climatological liklihood of the severe icing scenarios for the

geographical regions identified in Section 2. This would establish the probability of severe icing for these regions. By performing the identical procedure for areas of severe icing for which measurements exist we can establish the validity of this approach and establish whether or not the data base is representative of the world-wide icing environment.